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A comparison between oil, battery electric vehicles, and electric roads for Danish road transport in terms of energy, emissions, and costs

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July 2016

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Key Messages

Transport is the Largest Part of the Energy System

A. Transport demand is increasing: it increased by almost 50% in Denmark from 1980-2010.

B. The renewable energy penetrations achieved to date in transport are relatively low: Denmark has a renewable energy share of over 50% in electricity and heating, but only 5% in transport.

C. Vehicles are the most expensive component in the energy system: in 2010, vehicles accounted for ~45% of the annual energy system costs in Denmark which equates to ~€10 billion/year (see Figure 3[*]).

D. Transport is the most expensive sector in the energy system: in 2010, the transport sector, which includes vehicles, fuels, and other costs, accounted for two-thirds of the annual energy system costs in Denmark (see Figure 3), with electricity and heating making up the remainder.

Electric Cars are Much Cheaper with Smaller Batteries

E. Batteries are the most expensive part of an electric car and account for more of the annual costs than all of the other major costs combined (see Figure 2).

F. If battery costs are excluded, then electric cars are already cheaper than conventional diesel and petrol cars (see Figure 2).

Electric Roads are Relatively Cheap Compared to Vehicle Costs

G. Electric roads (eRoads) supply electricity to the vehicle while it is moving, like an electric train or trolley bus.

H. The hypothesis in this report is that eRoads should be installed on the major routes on the road network between densely populated areas, so that electric vehicles can use electricity from the road instead of relying on an on-board battery. By doing so, the battery capacity required in the electric vehicle can be significantly reduced.

I. Many different eRoad technologies are currently in the research, development, and demonstration phases: 17 were identified in this study (see Table 1 and Table 2). Two primary methods of charging for electric roads are being developed: conductive and inductive.

J. Elonroad (www.Elonroad.com) is used as a benchmark in this study for the cost and performance of an electric road: in most cases, conservative assumptions are used here since Elonroad is currently in the research and development phase, with the first demonstration due to begin in early 2017 (see Table 5). For example, it is assumed that Elonroad will have an investment cost of €1.5 million/km-one-way, which is double their current forecasts, and a lifetime of 10 years is applied, even though many of the components will last much longer.

K. An electric road network for Denmark is presented in this study (see Table 4 and Figure 7) which assumes that everyone in Denmark will be within 50 km of an eRoad route. To do so, eRoads are installed on two lanes over 1350 km of roadway, so in total 2700 km of eRoads are installed.

L. The total annual cost of installing and maintaining 2700 km of eRoad infrastructure in Denmark is ~€500 million/year (see Figure 8). In comparison, the total annual cost of vehicles

[*]All Figures and Tables referred to here are in the full report

in Denmark is ~€10 billion/year (see Figure 3), so the eRoad infrastructure represents a relatively small cost in the transport sector.

This Study Compares Electric Roads with Oil and Battery Electric Vehicles

M. The 2010 Danish energy system is used here to compare oil, eRoad, and battery electric vehicles.

N. Costs from two different years are applied to the 2010 Danish energy system: historical costs based on the year 2010 and forecasted costs for the year 2050, primarily since some of the key costs in the energy system are likely to change significantly between 2010 and 2050 such as fuel, CO_2, battery, and renewable energy costs.

O. Cars, trucks, and buses are all electrified in some of the eRoad scenarios, but only cars are electrified in the battery electric vehicle scenarios, since the cost of on-board batteries is extremely high to achieve sufficient range in trucks and buses.

P. Electric vehicles in the eRoad scenarios have a range of 150 km, while battery electric vehicles have a range of 300 km or more.

eRoads are Cheaper than Batteries in All Scenarios & than Oil in the Future

Q. eRoads cost more than oil today based on 2010 costs (see Figure 9), but due to 1) increasing fuel and CO_2 costs combined with 2) reducing battery and renewable energy costs, eRoads are cheaper than oil based on the 2050 costs (see Figure 12).

R. eRoads are cheaper than battery electric vehicles in every scenario considered here for Denmark (see Figure 9 and Figure 12): the additional investment required to construct eRoads is cheaper than the additional cost of extra storage capacity in the vehicle, even after assuming significant reductions in battery costs in the future (see Figure 12).

S. eRoads and battery electric vehicles are more efficient and less polluting than oil transport, primarily because the vehicles themselves are more efficient, but also because their batteries can facilitate more renewable electricity such as wind power (see Figure 10 and Figure 13).

T. eRoads can reduce the energy demand and carbon dioxide emissions more than battery electric vehicles, since they can facilitate the electrification of heavy-duty transport such as trucks and buses (see Figure 10 and Figure 13).

Recommendations: eRoads are One of the Most Promising Alternatives to Oil

U. Policymakers should allocate more funding to analyse, develop, and demonstrate electric roads, since the results here indicate that they are a very promising technology for the cost-effective decarbonisation of road transport.

V. Industry should release key cost and performance data (see Table 5) based on the upcoming demonstrations of various electric road technologies, to validate the conclusion that eRoads are a low-carbon and cost-effective alternative for road transport in the future.

W. Key stakeholders in the electricity, vehicle, road, and construction sectors will need to combine their skills and backgrounds to enable the implementation of electric roads. Ultimately, this could lead to a new institution, like a conventional Transmission System Operator in the electricity sector, that is solely responsible for the implementation, operation, and maintenance of the eRoad infrastructure.

Executive Summary

Electric vehicles have recently become one of the most promising decarbonisation solutions for the transport sector. They are more efficient than conventional oil-powered vehicles and if a renewable electricity supply is provided, then they can operate without any carbon dioxide emissions. However, the major drawback is the relatively high cost of the battery, which typically limits the affordable range of an electric car to less than 200 km and is also a major barrier for the electrification of heavy-duty transport such as trucks and buses. For example, the battery in an electric car typically costs more than all of the other major costs considered here (in Figure A) and **if the battery cost is excluded, then electric cars would already be cheaper than existing petrol and diesel cars today** (see Figure A). However, when the battery costs are included, the price of the vehicle can almost triple, depending on the required range, which significantly reduces the affordability of electric cars. The aim in this study is to analyse a new low-carbon solution for transport: electric roads (eRoads), which work in conjunction with electric vehicles to overcome the relatively high cost of these batteries and can potentially facilitate the electrification of heavy-duty transport such as trucks and buses. Other heavy-duty transport, such as ships and aeroplanes, are not included here since they do not use the road network and will most likely require some form of liquid or gaseous fuel in the future [1].

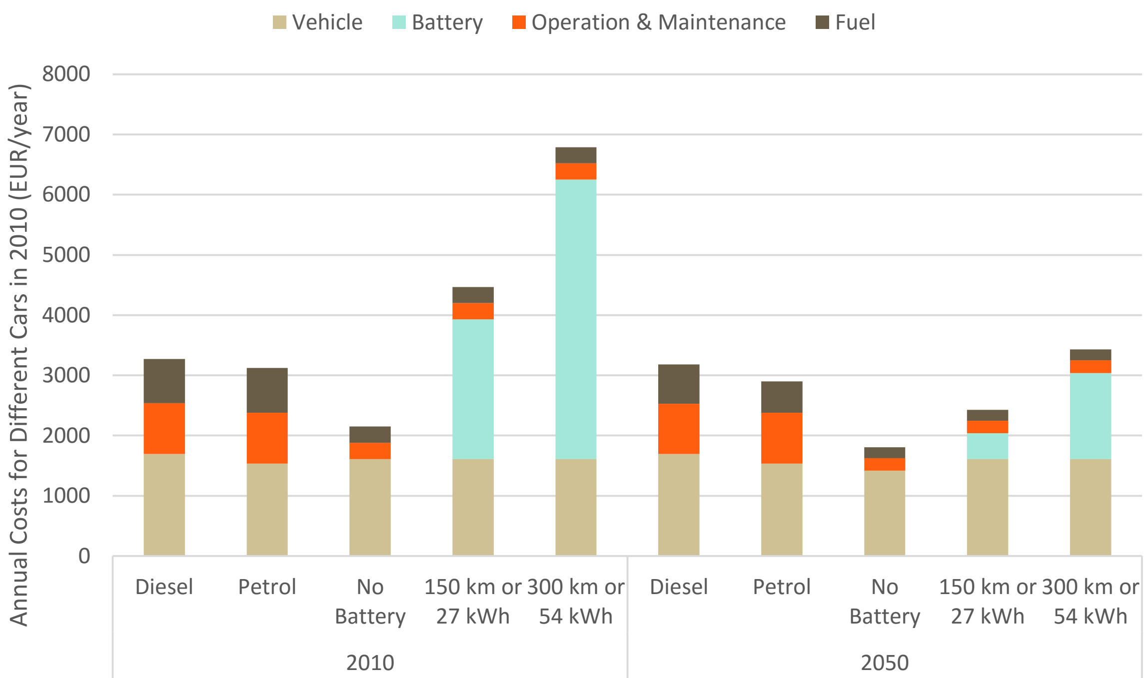

Figure A: Annual socio-economic costs of a diesel, petrol, and electric car in 2010 and 2050 [2], excluding carbon dioxide costs, taxes, and subsidies. The calculation assumes an average annual mileage of 20,000 km. The vehicle costs assumed for this calculation are provided in Table 8 and Table 9 of the Appendix and the investments are annualised based on an interest rate of 3% and a fixed-rate repayment.

eRoads deliver electricity to the vehicle as it moves, like an existing electric train or trolley bus, rather than storing the electricity in an on-board battery. In this study, **eRoads are installed on all major routes that connect densely-populated urban areas, such as cities and large towns, so electric vehicles do not require a battery to travel between these points**. For example, to travel between the city centres of Paris and Berlin in a world with eRoads, an electric car would only need the battery to travel ~50 km from the centre of these cities to the primary roads that circulate each one, since the remaining ~1000 km could be provided by electricity directly from the vehicle. By doing so, eRoads could significantly reduce the battery capacity required for an electric vehicle, since the vehicles would only need enough on-board storage to reach the main route rather than to reach their final destination. Furthermore, the battery can recharge while it is connected to the eRoad, so the vehicle will have its full range when it leaves the electrified portion of the road network. In this example, it means that an electric vehicle travelling from Paris to Berlin would arrive on the edge of Berlin with a full battery to reach its final destination within the city.

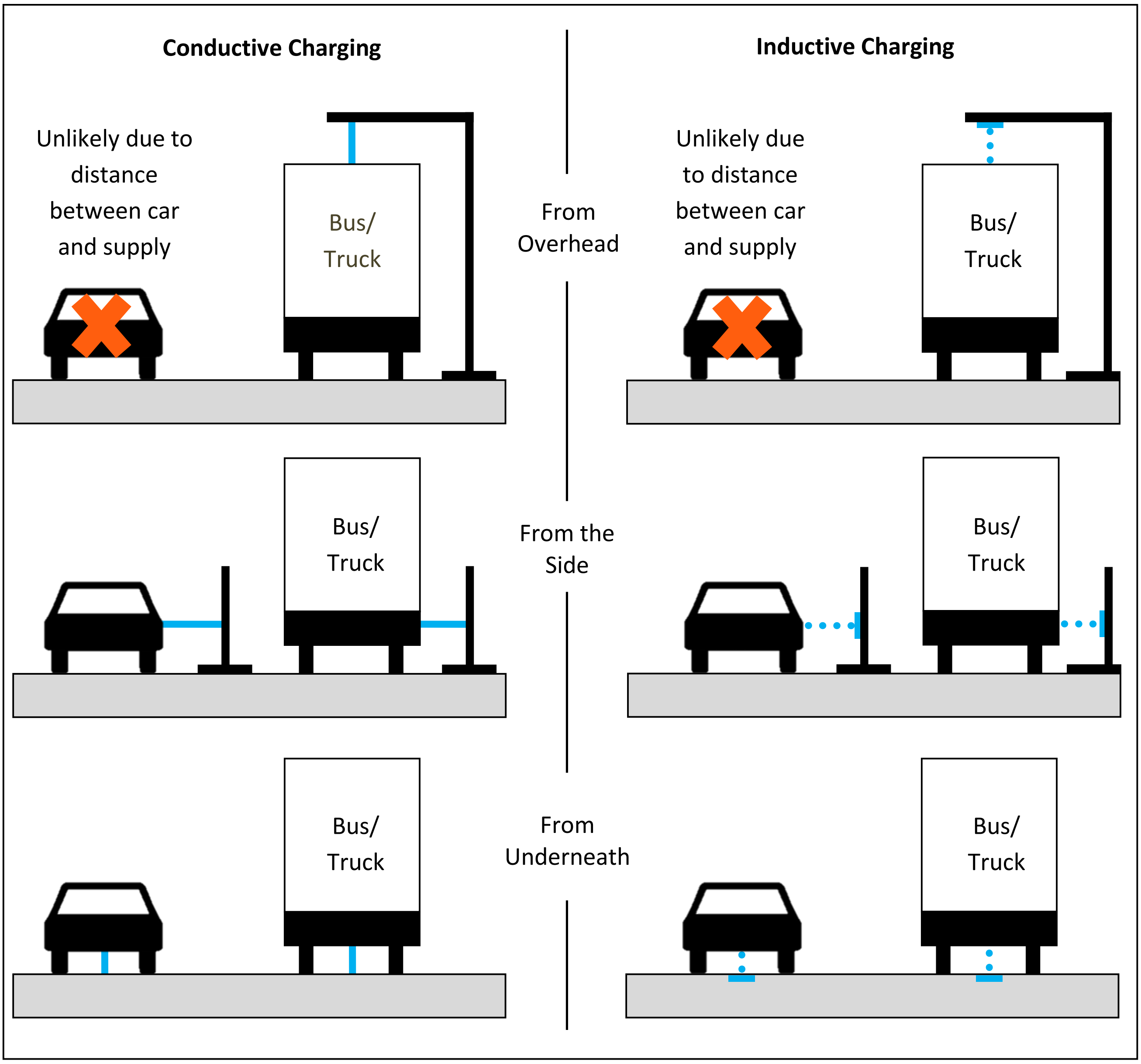

Figure B: Different concepts currently being investigated to electrify roads: inspired by the illustrations in [3].

eRoad technology is still in the early stages of development, so there are a variety of solutions in the research, development, and demonstration phases. In total, 17 different eRoad proposals were identified in this study and from this it was clear that two approaches are evolving to connect the road and the vehicle (see Figure B): **conductive charging where the electric vehicle is physically connected to the road, and inductive charging where electricity is transferred wirelessly via an electromagnetic**

field. As displayed in Figure B, the connection from the road can be from above, below, or at the side of the vehicle for both conductive and inductive charging. This study includes an overview of the various eRoad technologies being developed, but these are not compared with one another since the aim here is not to identify the optimum solution at present. Instead, one of the technologies currently in development, Elonroad (www.Elonroad.com), is used as a benchmark for the cost and performance assumptions applied in the analysis.

Elonroad is a conductive eRoad technology that connects below the vehicle. **A connection from below the vehicle is specifically chosen here since these solutions can electrify light- and heavy-duty transport at the same time**, which is considered a key benefit of eRoads over batteries. Based on various discussions with the developer of Elonroad, a number of important assumptions are defined for eRoads in the analysis (see Table A). Relatively conservative assumptions are chosen since Elonroad is still in the early stages of development, so it is possible that some unforeseen costs will be encountered during its implementation.

Table A: Key assumptions for eRoad infrastructure in this study, based on the Elonroad system [4]**.**

Investment for a full installation, including electric grid costs (M€/km One Way)	1.5
Lifetime of Infrastructure (years)	10*
Interest Rate	3%
Fixed O&M (% of Investment)	1%
Conductive pick-up for *Cars&Vans* (€)	2000#
Conductive pick-up for *Buses&Trucks* (€)	10,000#
Efficiency transferring electricity from the road to the vehicle (%)	90%

***A 10-year lifetime is relatively conservative, since many of the components will last longer than 10 years.**
#The pickup costs are likely overestimated, since a recent study suggest that a pickup is currently available for trucks at a cost of €5000 for a conductive connection. The lifetime of the conductive pick-up is assumed to be the same as the vehicle (see Table 8 in the appendix).

Denmark is used as a case to analyse the economic viability of eRoads. To begin, a model of the 2010 Danish energy is developed in an energy systems analysis model, EnergyPLAN (www.EnergyPLAN.eu), which simulates the electricity, heating, and transport sectors of the energy system on an hourly basis over a single year. The 2010 model acts as a reference so various alternatives can be benchmarked against a fixed starting point. After creating the *2010 Reference* model based on historical data, it became apparent that **vehicles account for approximately 45% of the annual energy system costs in Denmark**: this is very significant for eRoads, since one of its key benefits over battery electric vehicles (BEVs) is the reduced vehicles costs due to a smaller on-board battery. Similarly, **the entire transport sector, which includes vehicles, fuel, and other various costs, accounted for two-thirds of the annual energy system costs in Denmark in 2010**. Therefore, any changes to the transport sector will have a significant impact on the overall cost of the energy system.

The eRoad network proposed for Denmark in this study is displayed in Figure C. A key assumption during the design of the network is that everywhere in Denmark should be within a 50 km distance of an eRoad route. Correspondingly, it is assumed that eRoad electric vehicles have a range of 150 km, which is three times the distance required to reach an eRoad route, and it is approximately half of the range assumed for conventional battery electric vehicles. eRoads will require a large upfront investment to be installed on the main routes of the road network, so **the economic comparison between eRoads and battery electric vehicles can be viewed as a balance between the additional cost of constructing eRoads, and the cost savings due to the smaller batteries required in the eRoad electric vehicles**.

Figure C: Map of routes where eRoads are proposed in this study for Denmark (see Table 4 also).

The 2010 Danish energy system reflects an oil-based transport sector, since over 99% of the fuel consumed for transport that year was oil. Using this as a starting point, various eRoad and electric vehicle scenarios are compared against this 'oil' reference. Using the EnergyPLAN model, it is possible to quantify the impact of implementing these solutions based on three different criteria:

- **Primary Energy Supply:** Reflects the **efficiency** of the energy system by measuring the total energy consumed over a single year across all sectors including electricity, heat, and transport.
- **Carbon Dioxide Emissions:** Reflects the **environmental** impact of the energy system by measuring the total annual carbon dioxide emissions produced.
- **Energy System Costs:** Reflects the **economy** of the energy system based on the total annual socio-economic cost including investment, fuel, CO_2, operation, and maintenance costs.

The cost of some key components in the energy system is expected to change significantly over the coming decades. For example, fossil fuel and CO_2 prices are expected to increase, while batteries and renewable energy costs are expected to decrease. Each of these changes will have a significant impact on the economy of electric vehicles, so two different datasets are used for the costs in this study. One is based on historical costs from the year 2010 and one is based on forecasted costs for the year 2050. These will therefore represent the economy of each scenario based on today's costs (i.e. 2010) compared to the economy based on future costs (i.e. 2050). The *2010 Reference* Danish energy system forms the basis of the analysis for both cost datasets, and using this oil, eRoad, and Battery Electric Vehicles are compared with one another based on the three criteria mentioned above.

Figure D indicates that **electric vehicles will cost more than oil transport based on the 2010 costs**: the costs are increased by ~20% for eRoads and by ~40% for the BEV scenario compared to the *2010 Reference* scenario, which are primarily due to an increase in the vehicle costs. As mentioned previously, vehicles represent approximately 45% of the annual energy system costs in 2010, and as outlined in Figure A, electric cars are more expensive than oil vehicles in 2010. The additional cost of these electric vehicles is the primary cause of the increased costs in the eRoad and BEV scenarios, but as mentioned earlier, these are expected to decrease in the coming decades.

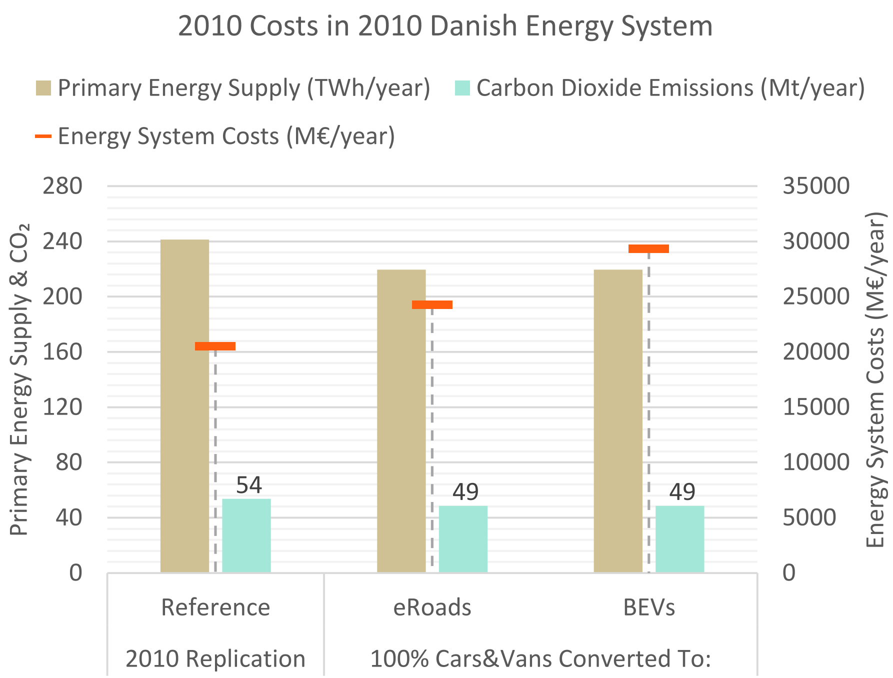

Figure D: Primary energy supply, carbon dioxide emissions, and annual energy system costs for the *Ref 2010* scenario with various penetrations of eRoad and battery electric vehicles, based on the scenarios presented in Table 3 and the eRoad infrastructure proposed in Table 4. The fuel and vehicle costs as based on the year 2010 (see Table 6).

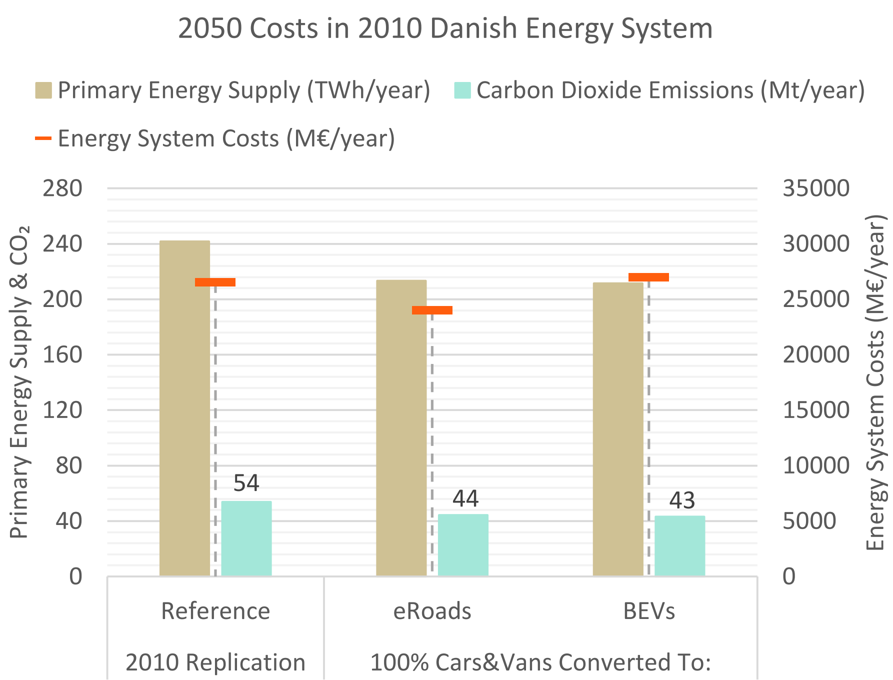

Figure E: Primary energy supply, carbon dioxide emissions, and annual energy system costs for the *Ref 2010* scenario with various penetrations of eRoad and battery electric vehicles, based on the scenarios presented in Table 3 and the eRoad infrastructure proposed in Table 4. The fuel and vehicle costs as based on the year 2050 (see Table 6).

Using the 2050 costs, the results are repeated once again for the 2010 Danish energy system. The results in Figure E indicate that **if costs evolve as expected between now and 2050, then eRoads will be a cheaper form of road transport than both oil and battery electric vehicles**. The eRoad scenario is approximately 10% cheaper than both the *2010 Reference* and BEV scenarios: increasing fuel and CO_2 costs have made the *2010 Reference* more expensive, but these have been counteracted in the eRoad and BEV scenarios by falling battery and renewable energy costs. Importantly, the eRoad scenarios are also cheaper than the BEV scenarios using both 2010 and 2050 cost assumptions, suggesting that **eRoads are a cheaper form of electrification than on-board batteries in both the short- and long-term for Denmark based on the design proposed here**.

An important benefit of electric vehicles for the energy system is the additional flexibility that they introduce, since the electricity sector can use their batteries to balance the production of intermittent renewable electricity such as wind and solar. With 2010 costs, fossil fuels were often cheaper than renewable electricity so these benefits were not utilised as much, but with the 2050 costs, renewable electricity becomes relatively cheap compared to fossil fuels so more wind power is installed in the Danish energy system. This wind power can use the flexibility in the batteries of the electric vehicles to balance its supply and demand while reducing costs, as well as reducing energy consumption and carbon dioxide emissions.

In all scenarios considered here, the eRoad and BEV scenarios require less energy and produce less CO_2 than the corresponding oil scenario. Both eRoads and BEV perform very similarly to one another in terms of energy and carbon reductions: using the 2010 costs, both scenarios reduce the primary energy supply and carbon dioxide emissions by approximately 10% (see Figure D), and with the 2050 costs these reductions are increased to approximately 15-20%. These reductions occur since electric vehicles are more efficient than oil vehicles which are typically powered by petrol or diesel, and because electric vehicles also enable the integration of more renewable electricity such as wind and solar power. Therefore, **electric vehicles in the form of either eRoads or Battery Electric Vehicles are more efficient and produce less CO_2 then oil powered vehicles using both today's costs, and forecasted costs for 2050**. In addition, one of the key advantages with eRoads is that they could potentially facilitate the electrification of heavy-duty transport such as trucks and buses and if they do, then they will decrease the energy consumption and CO_2 emissions even more.

In summary, the eRoad and BEV scenarios will both improve the efficiency and environmental impact of transport, something which will increase the cost of the Danish energy system in the short-term, but based on current price forecasts for batteries, fuels, CO_2, and renewable energy, the eRoad scenario will be a cheaper form of road transport in 2050. There are still many uncertainties and barriers for eRoads, since they are still at a relatively early stage of development, but the results from this study suggest that they should be considered as primary candidate for the decarbonisation of the transport sector and energy system in the future.

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1. Introduction

The electricity and heat sectors are currently experiencing rapid growths in renewable energy production, but the transport sector is still almost exclusively dependent on oil. New solutions are urgently required to replace this oil consumption in the transport sector, especially considering the global push for decarbonisation. This study presents one such solution, electric roads (eRoads), which are used to supplement battery electric vehicles (BEVs). The current status of the concept is presented and then the impact of implementing electric roads is quantified in terms of energy consumption, carbon dioxide emissions, and cost. Denmark is used here as a case study to ensure the assumptions applied are connected to a real world case, while the assumptions for the eRoad technology itself are based on the most recent costs reported by a variety of developers, primarily based on initial prototypes and pilot projects in Sweden. The results suggest that eRoads are an economically viable alternative if they can be implemented at the costs assumed here.

The demand for oil in the transport sector has grown substantially in recent decades: for example, as displayed in Figure 1, the demand for oil in Denmark has grown by almost 50% in 30 years between 1980 and 2010. Transport is now the largest sector in the energy system in Denmark, accounting for approximately one-third of all energy consumed, thus signifying the importance of developing solutions to decarbonise the sector going forward. Progress to date is relatively slow, with the electricity and heat sectors developing new low-carbon solutions at a much faster rate. Renewable energy currently produces over 50% of both the electricity and heat consumed in Denmark, but the transport sector still has a renewable energy penetration of approximately 5% [5]. In the broadest sense, the most common solutions presented to date to decarbonise the transport sector are electric vehicles, biofuels, hydrogen, and electrofuels (power-to-fuel). However, each of these are facing some significant barriers:

- Electric vehicles need to overcome the relatively high cost of batteries (discussed in more detail later).
- The fundamental sustainability of biofuels is still in question [6], [7], particularly as large quantities are consumed.
- Hydrogen is relatively inefficient [8], [9] and it will require a completely new fuel distribution infrastructure which is likely to be much more expensive than continuing with oil.
- Electrofuels are also relatively inefficient, but cheaper than hydrogen since they do not require any major new upgrades to the fuel distribution infrastructure. However, they will require some ground-breaking developments in electrolyser technology to be produced a cost comparable to oil in the coming decades.

This historical growth in demand, the scale of the transport sector today, and the level of renewable energy penetration achieved demonstrates the urgent need for new developments in low-carbon solutions for the transport sector, such as eRoads.

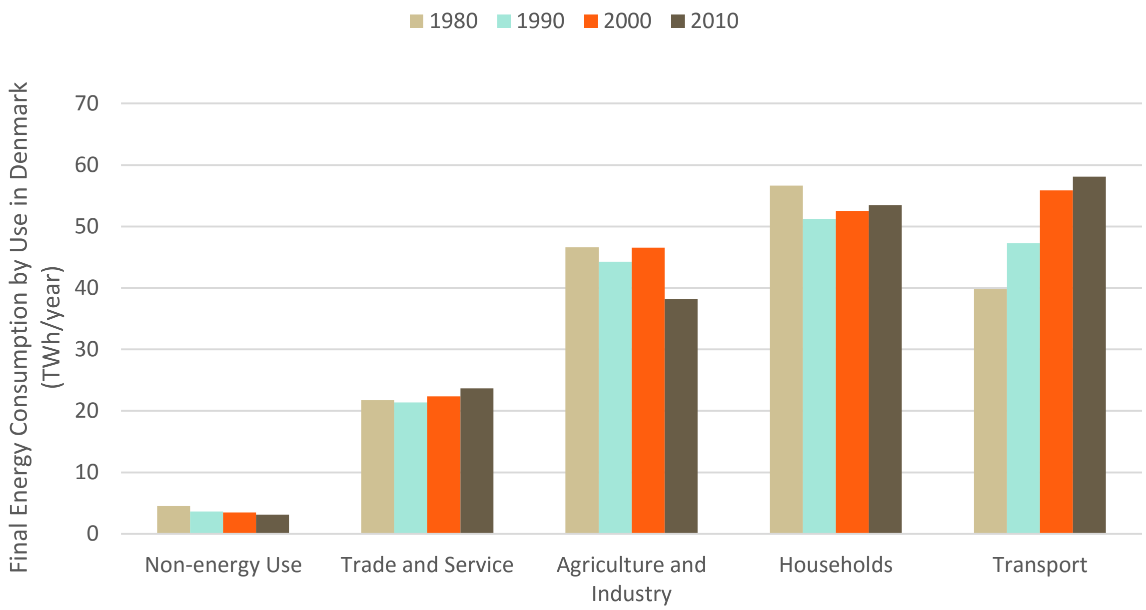


Figure 1: Total primary energy consumption in Denmark divided by sector from 1980 to 2010 [5].

1.1. The Principle of eRoads

Electric roads (eRoads) are one concept that could contribute to the decarbonisation of transport, more specifically road transport, as long as they are supplemented by a decarbonised electricity system. The fundamental principal is that electric vehicles can use electricity directly from the electric grid as they travel along the road, rather than relying on the storage medium of a battery. If eRoads are installed on the major links that connect highly-populated urban centres together, then it will be possible to use the eRoad technology for long-distance journeys (defined here as more than 50 km) rather than using an on-board battery. This could significantly reduce the size of the battery required for an electric vehicle, since it would only need sufficient capacity to reach the eRoad infrastructure, rather than the final destination. The importance of this is evident when considering the cost breakdown for a typical electric vehicle.

Figure 2 presents the annual cost of a typical diesel, petrol, and electric car, with and without the battery costs included. If the battery is excluded, then electric cars are already cheaper than conventional diesel or petrol cars today because the drivetrain, fuel, and maintenance costs associated with electric cars are actually cheaper than conventional vehicles already. However, as displayed in Figure 2, the battery costs can double or triple the annual cost of the electric car, depending on the range that is required. In fact, the battery represents the single largest cost associated with electric cars today, costing even more than all of the other costs considered in Figure 2 combined. If eRoads can reduce the battery capacity required, then they could potentially make electric cars more affordable since they will reduce the costliest component associated with an electric car. They key question in this study is if these savings are high enough to justify the initial cost of the eRoads. Figure 2 has demonstrated the savings potential at a vehicle level, but Figure 3 indicates that this will also have a significant impact on the overall energy system.

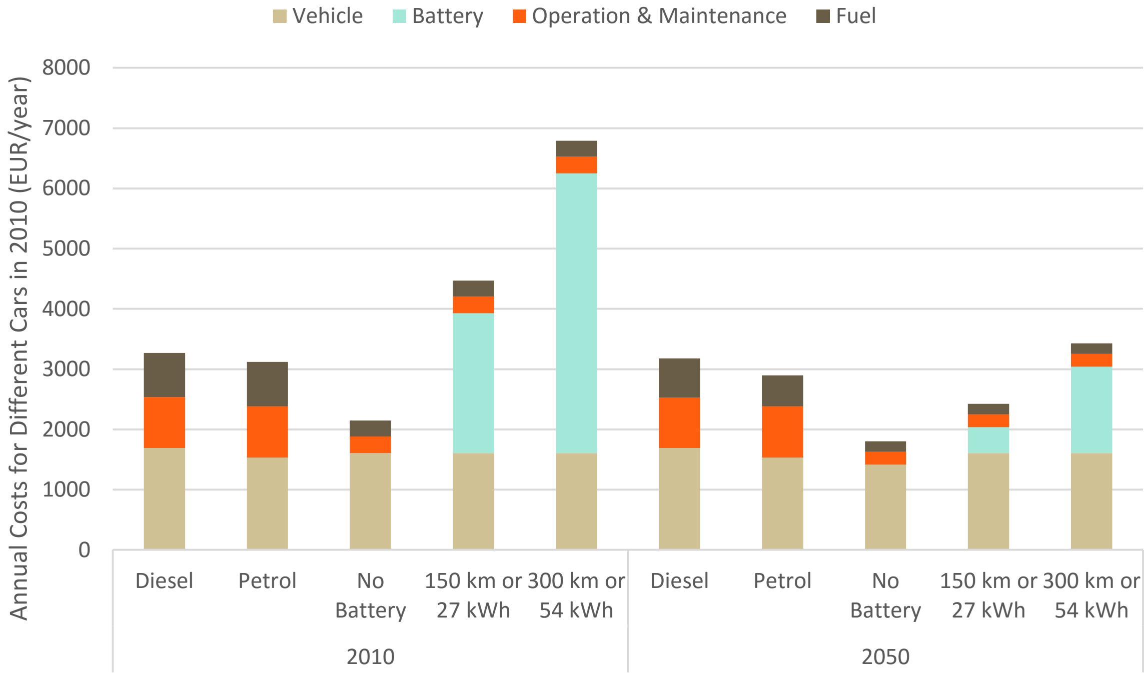


Figure 2: Annual socio-economic costs of a diesel, petrol, and electric car in 2010 and 2050 [2], excluding carbon dioxide costs, taxes, and subsidies. The calculation assumes an average annual mileage of 20,000 km. The vehicle costs assumed for this calculation are provided in Table 8 and Table 9 of the Appendix and the investments are annualised based on an interest rate of 3% and a fixed-rate repayment.

Energy is sometimes defined in terms of the key end-user demands: electricity, heating (and cooling), and transport. The annual cost of these three sectors for the Danish energy system is presented in Figure 3 based on the year 2010, using results from the CEESA study [10]. A cost breakdown like this reveals the most important issues to consider for long-term energy planning, since it demonstrates where and how money is being spent in the energy system. Heat and electricity is currently provided by 'fuel-based' technologies such as boilers and power plants. The investment required for these technologies is relatively low compared to the variable cost (i.e. fuel, O&M, and CO_2) their lifetimes. As displayed in Figure 3, the result is that heat and electricity spend almost twice as much on fuel each year than they do on investments. So these are fuel-dominant sectors. In contrast, the transport sector is an investment-dominant sector: Figure 3 demonstrates the relative scale of the transport sector and its individual parts. Vehicles represent the single largest cost component in the energy system today, accounting for approximately 45% of the total annual energy system costs in 2010. Therefore, any change in vehicle costs will have a major impact on the overall energy system costs, which is important in the context of eRoads considering one of the key aims is to reduce the cost of electric vehicles in the future. Similarly, the scale of these vehicle investments suggest that there is a huge potential to obtain the upfront investment in the transport sector for a common infrastructure like eRoads, if it is necessary for the initial construction.

Figure 3 also reiterates the relatively large scale of the transport sector as a whole, but from a cost perspective (Figure 1 demonstrated this from an energy perspective). The total annual energy system costs for transport, which are the road vehicle and transport-fuel costs combined, account for two-thirds of the total annual energy system costs in 2010. Again, this reinforces the importance of developing new low-carbon technologies such as eRoads for the transport sector, since changing the transport sector will have a major impact on the overall demand (Figure 1) and cost (Figure 3) for energy.

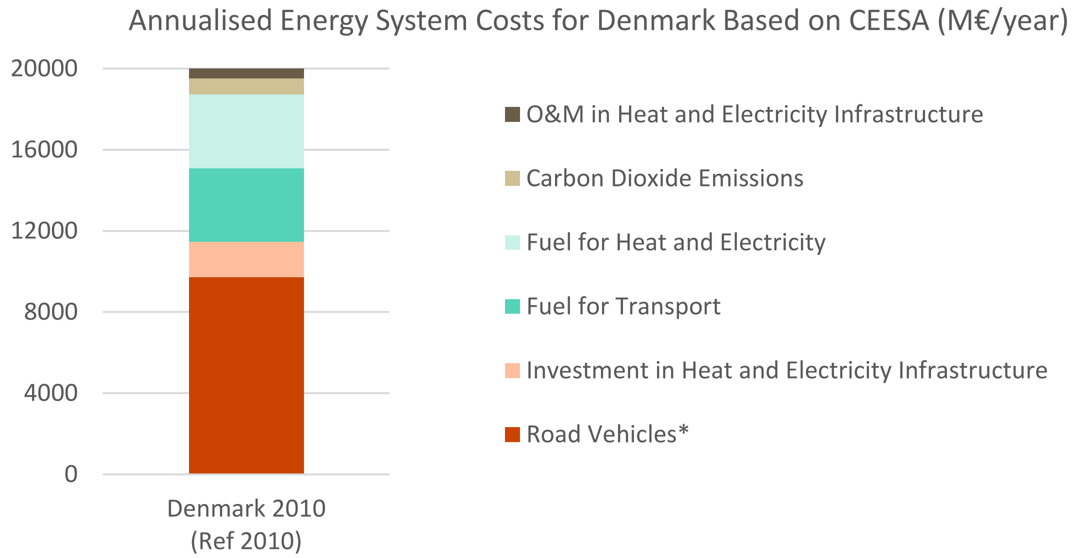


Figure 3: Annual energy system costs in Denmark based on the 2010 energy system [10]**. *Includes investments and operation and maintenance (O&M) costs for road vehicles. Bikes, motorbikes, ships, trains, and aeroplanes are not included in the vehicle costs due to a lack of sufficient data.**

1.2. eRoad Technology

One of the major challenges in an earlier version of this study from 2012 was identifying how an electric road could be implemented and the related costs [11]. Since then, a variety of new eRoad concepts have been developed worldwide, using two primary methods to connect the roadway to the vehicle: conduction and induction. As presented in Figure 4, the electric connection to the vehicle can be provided from above, beside, or below the vehicle depending on the preferred configuration. A summary of current developments for conductive technologies is provided in Table 1 and for inductive in Table 2.

With conduction, there is a physical connection between the road and the vehicle similar to the many mainstream electric trains, trams, and trolley buses. As a result, the technology is relatively mature although it requires some modifications to be applied to road vehicles. There is no physical connection for the induction system; instead, electricity is transferred via a magnetic field. There are some demonstration and pilot projects for this technology, but it is relatively immature compared to conductive charging (see Table 1 and Table 2).

Both conductive and inductive charging can use various approaches to connect to road vehicles (see Figure 4). Initially, many concepts connected to the vehicle from overhead, which is likely due to the similarities with existing rail and tram infrastructure. However, the majority of existing developments are now connecting to the vehicle from underneath, since the major advantage is that both light- and heavy-duty vehicles can then also utilise the infrastructure.

The aim in this study is not to identify the optimum eRoad technology currently under development, since it is currently unclear which type of solutions will become mainstream in the future. For example, key stakeholders in Sweden, where the most concepts are being developed at present, recently produced two reports highlighting how both a conductive [12] and inductive [13] eRoad system could be implemented, rather than defining which one is preferred. However, to create some consistency in the assumptions applied here, one specific concept, the Elonroad concept [4], is assumed during this analysis to act as a point of reference when defining the costs and efficiencies for the future.

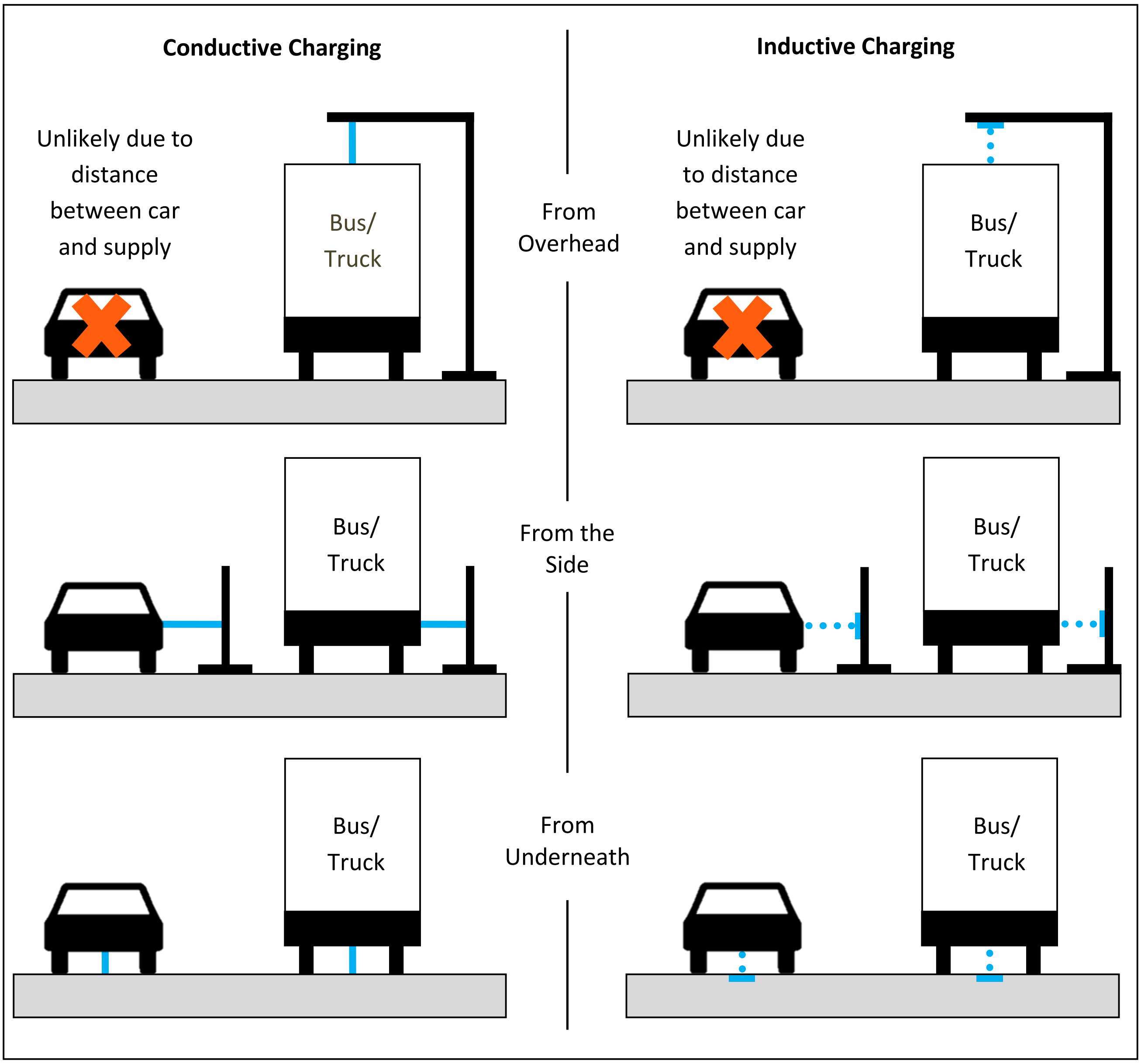


Figure 4: Different concepts currently being investigated to electrify roads: inspired by the illustrations in [3]**.**

Table 1: Overview of conductive eRoad technologies identified.

Name	Company	Location of Connection and Type of Vehicles Considered	Status	Country	Reference
eHighway	Siemens and Scania	Overhead Conductive for Trucks	Trials ongoing, 2 km demonstration in Sweden, and 1 mile demo in California	Sweden and USA	[14]–[16]
Boost Charging Technology	ABB	Overhead Conductive for Stationary Buses	Pilot Project	Switzerland	[17]
Unknown	Toyohashi University of Technology	Conductive via Wheel for All Road Vehicles	Demonstrated in the Lab	Japan	[18]
APS / SRS / Innorail	Alstom	Underneath Conductive for Tram, expanding to Road Vehicles	Operating in trams in four cities, with 62 km of track installed	France	[19]–[21]
Slide-In	Viktoria Swedish ICT, Volvo GTT, Scania CV, Bombardier, Vattenfall, The Swedish Transport Administration, Projektengagemang (Svenska Elvägar AB), Lund University, KTH Royal Institute of Technology and Chalmers	Underneath for All Vehicles	Feasibility Study estimating the cost, efficiency, and technical design to install an eRoad between Stockholm and Gothenburg	Sweden	[12], [22]
Unknown	Volvo, Alstom, Lund University, and the Swedish Energy Agency	Underneath Conductive for Trucks	Trials ongoing using a 400 m test track	Sweden	[23], [24]
Elväg	Elväg AB, KTH University, NCC, Swedish Energy Agency, and Arlandastad Holding AB	Underneath Conductive for All Vehicles	Demonstrated on a test track and 2 km pilot under construction	Sweden	[25]
Elonroad	Elonroad, with support from the Swedish Energy Agency, Lund University, Volvo and Kraftringen Energy Company	Underneath Conductive for All Road Vehicles	Demonstrated in the Lab: Pilot scheme under development	Sweden	[4]

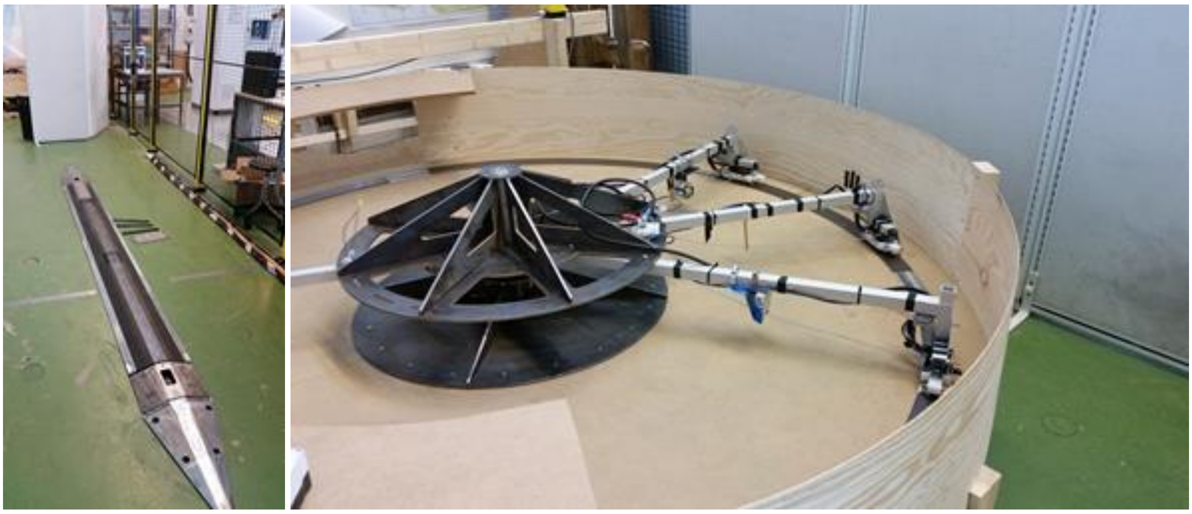
Table 2: Overview of inductive eRoad technologies identified.

Name	Company	Location of Connection and Type of Vehicles Considered	Status	Country	Reference
Electric Highways	Highways England	Underneath for all Vehicles	Feasibility study	England	[26]
OLEV	OLEV	Underneath for Cars and Buses	Trials Ongoing	South Korea	[27]
Primove	Bombardier	Underneath for All Road Vehicles and Trams	Numerous One-off Applications Implemented	Belgium and Sweden	[28]
Slide-In	Viktoria Swedish ICT, Volvo GTT, Scania CV, Bombardier, Vattenfall, The Swedish Transport Administration, Projektengagemang (Svenska Elvägar AB), Lund University, KTH Royal Institute of Technology and Chalmers	Underneath for All Vehicles	Feasibility Study estimating the cost, efficiency, and technical design to install an eRoad between Stockholm and Gothenburg	Sweden	[13], [22]
Unknown	Polito	Underneath for Cars and Vans	20 kW prototype in a lab	Italy	[29], [30]
Wireless Power Road	INTIS	Underneath for All Vehicles	Test track developed	Germany	[31]
Unknown	Nissan	Underneath for All Vehicles	Demonstrated in the lab on a test track	Japan	[32]
Unknown	Oak Ridge National Laboratory	Underneath for Stationary Vehicles	Demonstrated in the lab	USA	[33], [34]
Halo	Qualcomm	Underneath for Stationary Vehicles	Unknown	Unknown	[35]

1.3. Elonroad

Elonroad is currently being developed in Lund, Sweden by a company of the same name [4]. It uses a conductive connection from underneath the vehicle and one of its key benefits is that it can be retrofitted on top of existing roads, rather than buried within the asphalt when the road is established. A narrow strip, which is displayed in Figure 5a, is laid in the centre of the road and connects to a pickup device attached to the vehicle. The centre strip is only activated when the vehicle passes over it and the system is currently functioning on a small scale in a lab at Lund University (Figure 5b) and on a small demo track at full scale [4]. A full-scale pilot project is currently under development in Lund, primarily for the city's bus network, and is expected to be operation by early 2017. Elonroad is used as an exemplar technology in this study for the following key reasons:

- It can be easily retrofitted onto existing roads, so it should be relatively easy to install at relatively low costs in comparison to other solutions.
- The vehicle is connected from underneath, so it is suitable for all road vehicles i.e. cars, buses, and trucks (see Figure 4)
- It is a direct connection technology, so it is expected to have a relatively high power transfer capacity (it can already deliver up 240 kW) and efficiency (97%)



(a) (b)

Figure 5: Elonroad: A conductive eRoad concept being developed at Lund University, Sweden [4], [36] **outlining (a) the conductive strip to be place on the road and (b) a rig in the lab testing the connection between the road and vehicle at high speeds.**

Using Denmark as a case study and the Elonroad technology as a point of reference, this study evaluates the socio-economic and technical impact of eRoads by comparing it with diesel, petrol, and battery electric vehicles. No existing study was identified that has made this comparison before, thus reflecting the novelty of the analysis here. The next section, which is the Methodology, presents the various scenarios and key assumptions in the analysis, while Section 3 presents the Results, which suggest that eRoads are indeed an economically viable solution for decarbonising road transport in the future.

2. Methodology

To begin, a model of the Danish energy system based on the year 2010 is constructed in the EnergyPLAN model [37], based on the 2010 model from the CEESA study [10]. It is referred to here as the "*Ref 2010*" scenario and since it is based on the year 2010, it reflects a scenario for conventional diesel and petrol vehicles since they accounted for over 99% of the fuel consumed that year. The rest were minor shares of biodiesel, bioethanol, and a very small amount of BEVs.

EnergyPLAN is an hourly model that simulates one year for the electricity, heating, cooling, industry, and transport sectors. It is purposely designed to be able model radical technological change, like the introduction of eRoads, while also ensuring that the energy system can balance large penetrations of intermittent renewable electricity like wind and solar power. EnergyPLAN has been developed at Aalborg University for over 15 years and it has been used to develop 95 peer-reviewed journal articles about the future development of the energy system [38]. The assumptions, architecture, code, and interface of the model are documented in detail on the EnergyPLAN homepage [37].

A detailed breakdown of the transport sector is created to compliment the energy system modelled in EnergyPLAN. As displayed in Table 7 in the Appendix, this includes the transport demand, number of vehicles, vehicle efficiency, and energy consumption for each mode of transport, which is further subdivided by fuel type. By creating such a breakdown, it is possible to develop various scenarios for the transport sector and thus compare eRoads with conventional technologies such as diesel, petrol, and BEVs. A systematic approach is used here (see Figure 6) so that any pre-defined mix of eRoads and BEVs can be analysed by altering the transport sector based on the assumptions presented in Table 7. Since the *Ref 2010* scenario already represents conventional diesel and petrol vehicles, the next step is to create scenarios for eRoads and BEVs.

2.1. Redesigning the Transport Sector

Firstly, a penetration rate for eRoads or BEVs must be defined (Figure 6). For the purposes of this explanation, we will assume that 50% of the cars in the *Ref 2010* scenario are converted to eRoad vehicles. Once the new penetration rate is defined, then 50% of the transport demand for conventional diesel and petrol cars is converted to eRoad cars. Using the vehicle efficiencies displayed in Table 7 in the Appendix, the new energy demand for cars is calculated by reducing the diesel and petrol consumption, and replacing it with electricity for the eRoad cars. The new energy mix is fed back into the EnergyPLAN model, where the eRoad vehicles are modelled using the electric vehicles module that is described in detail in Lund and Kempton [39]. EnergyPLAN also accounts for the losses that occur via the conductive connector between the road and the pickup device on the road. A 90% efficiency is assumed here based on the measured efficiencies reported for similar conductive eRoad technologies [12], which is relatively conservative since the Elonroad system is expected to have an efficiency closer to 97% [4], [36].

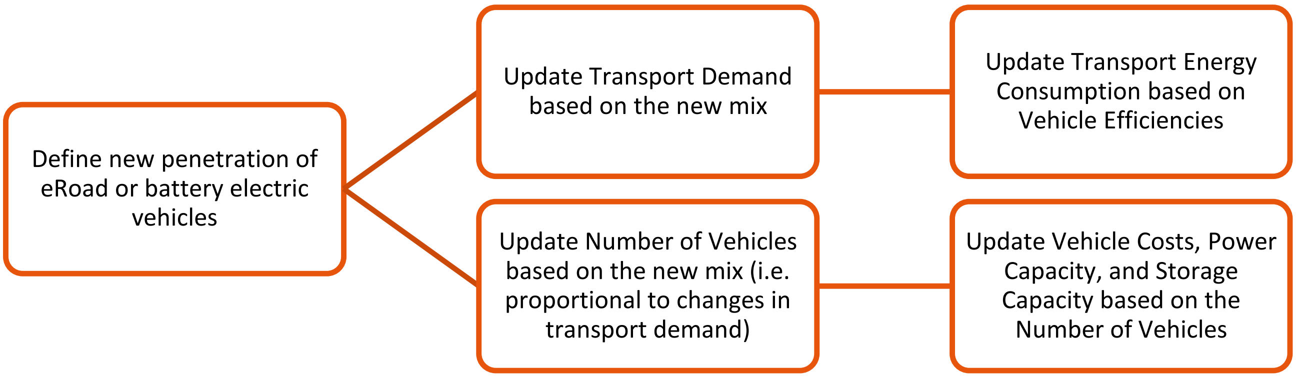


Figure 6: Steps in the methodology to adjust the transport sector based on a new penetration of eRoad or battery electric vehicles.

If 50% of the transport demand is converted to eRoads, then it is assumed that 50% of the cars are also converted from diesel and petrol to eRoad cars also. In other words, the assumption is that the transport demand changes proportionally to the number of vehicles. This is a relatively conservative assumption for the eRoad and BEV scenarios, since consumers with a relatively high mileage are likely to convert to electricity first since the fuel is cheaper in electric vehicles than in diesel and petrol vehicles (see Figure 2). Once the mix of vehicles is updated, then the vehicle costs are also updated based on the assumptions presented in Table 8 and Table 9 in the Appendix (note: the 2010 costs in the Appendix are applied first so the 2050 costs can be ignored for now, since these are discussed later as part of a sensitivity analysis). Similarly, the power capacity and storage capacity available in each electric vehicle is also updated in the EnergyPLAN based on the assumptions in Table 9 and Table 10 in the Appendix. Although the input for EnergyPLAN is the combined power and storage capacity for the entire electric vehicle fleet, the model uses an hourly transport distribution to account for the number of vehicles that are actually connected to the grid during each hour of the year [39].

After updating the *Ref 2010* scenario with the new transport energy mix, vehicle costs, power capacity, and storage capacity in the EnergyPLAN model, a simulation is run for the year 2010 with the new penetration of eRoad vehicles or BEVs. EnergyPLAN includes all other costs associated with the energy system, such as fuels, carbon dioxide, and maintenance costs. During the simulation, EnergyPLAN also checks if higher penetrations of wind power on the electric grid are cheaper once the eRoad vehicles or BEVs are implemented, since the wind could potentially utilise the new electricity storage capacity available in these vehicles. The results recorded from EnergyPLAN for each scenario are the annual energy system costs, the primary energy supply, and the carbon dioxide emissions, so each scenario can be evaluated from an economic, energy, and environmental perspective. Using this methodology, any pre-defined mix of eRoad vehicles and BEVs can be compared with the original *Ref 2010* (i.e. diesel and petrol) scenario. A list of the scenarios included in this study is provided in Table 3, along with the brief explanation of the scenario. The aim in this study is to analyse the long-term impact of implementing eRoads, so very large penetrations of vehicle conversions (i.e. 50% and 100%) are considered. Therefore, an eRoad infrastructure will be required to encourage these very high penetrations.

Table 3: Name and description of the scenarios analysed in this study.

Name of Scenario		Description of the Scenario
Ref 2010	*99% Oil**	The 2010 model of the Danish energy system based on historical data
eRoads	*50% Cars&Vans*	50% of the diesel and petrol cars and vans are converted to eRoad cars
	50% Cars&Vans and 50% Bus&Trucks	50% of the *Cars&Vans* and 50% of the *Buses&Trucks* are converted to eRoad vehicles
	100% Cars&Vans	100% of the diesel and petrol cars and vans are converted to eRoad cars
	100% Cars&Vans and 50% Bus&Trucks	100% of the *Cars&Vans* and 50% of the *Buses&Trucks* are converted to eRoad vehicles
Battery Electric Vehicles*	*50% Cars&Vans*	50% of the diesel and petrol cars and vans are converted to battery electric cars
	100% Cars&Vans	100% of the diesel and petrol cars and vans are converted to battery electric cars

***Battery electric buses and trucks are not included here, since the battery costs were deemed unrealistically expensive to justify the inclusion of this scenario.**

2.2. eRoad Infrastructure to Install

The population distribution in Denmark could be very suitable for the implementation of an eRoad solution, since the four largest cities are all located on one single highway: Copenhagen, Odense, Aarhus, and Aalborg. These are displayed in Figure 7 and approximately one-quarter of the Danish population lives within the boundary of these urban centres. A significant proportion of people would gain access to eRoad technology by installing the system on this road alone. However, rather than systematically analyse this, which could be included in future work, the approach here is to develop enough eRoad infrastructure to ensure beyond reasonable doubt that large conversions could take place, by simply expanding the eRoad to the point where it is deemed attractive for everyone. To ensure that enough eRoad infrastructure is available for high penetration rates like 50-100% (see Table 3), enough eRoad infrastructure is installed so that everywhere in Denmark is within 50 km of an eRoad. At the same time, it is also assumed that every electric vehicle that is designed to use these eRoads, including cars, vans, buses, and trucks, has a battery that enables them to travel 150 km on a single charge (see Table 10 in the Appendix), which is three times the furthest distance from an eRoad. This means that the eRoad vehicles can comfortably travel the shorter journeys beyond the eRoad infrastructure using the electricity stored in the battery. Using this principle, a new eRoad network is created for Denmark and used in the scenarios when evaluating the feasibility of eRoads in the future.

The resulting eRoad infrastructure designed to enable high penetrations of electric vehicles in Denmark is displayed in Figure 7 and Table 4: Four major routes are converted, including the road from Køge to Fehmarn, which is expected to become a major route in 2024 after the new tunnel connecting Denmark and Germany is completed. Furthermore, a series of secondary roads also have eRoad infrastructure installed in Jutland and Zealand, so in total 1350 km of road network is retrofitted with the Elonroad system. One lane is converted in each direction, so the total length of eRoad installed is 2700 km. It is likely that this is over-estimating the length of eRoad required, since the marginal benefits of installing eRoads on some of the secondary roads in Jutland and Zealand are likely to be very low, which is an important consideration when assessing the results later.

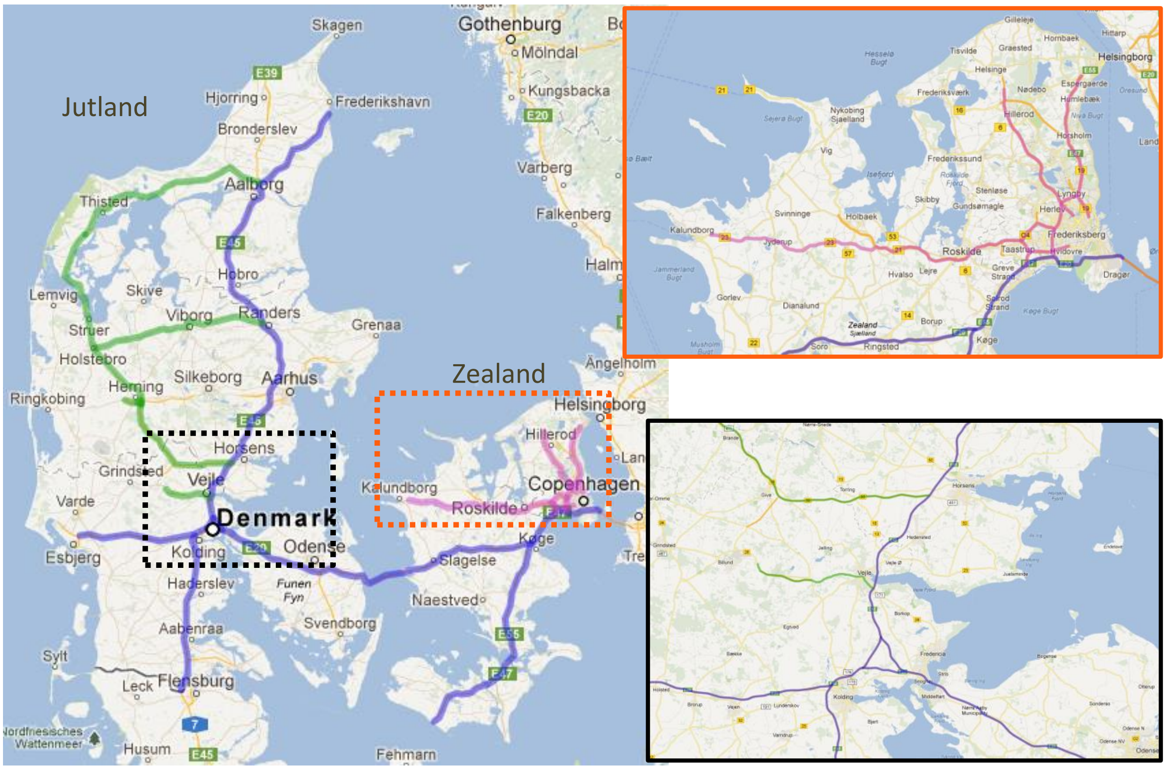


Figure 7: Map of potential routes where eRoads could be installed in Denmark (see Table 4 also).

Table 4: Distance of potential routes with an eRoad installed in Denmark (see Figure 7 also).

Route		Distance (km)		eRoad Required (km)	
Start	**End**	**Absolute**	**Cumulative**	**Absolute**	**Cumulative**
Major Intercity Routes					
Copenhagen	Frederikshavn	475	475	950	950
Fredericia	Esbjerg	85	560	170	1,120
Kolding	Flensburg	85	645	170	1,290
Køge	Fehmarn Bridge* (Lolland)	120	765	240	1,530
Jutland Branches					
Horsens	Herning	70	70	140	140
Herning	Aalborg (via Holstebro)	215	285	430	570
Holstebro	Randers	90	375	180	750
Vejle	Billund	25	400	50	800
Herning East	Herning West	10	410	20	820
Zealand Branches					
Copenhagen	Kalundborg	90	90	180	180
Copenhagen	Hillerod	35	125	70	250
Copenhagen	Helsingborg	35	160	70	320
Copenhagen	Ring/Connections	15	175	30	350
Total			**1,350**		**2,700**

***Køge to Fehmarn is not a major route at present, but it will become one in 2024 when the Fehmarn Belt connects Denmark to Germany via a tunnel in the Baltic Sea.**

The cost of the eRoad infrastructure is extremely difficult to estimate at present, since the concepts are still primarily at a lab or trial phase (see Table 1 and Table 2). An interview was held with the developers of Elonroad, who revealed that the aim is to install the technology at a cost of approximately €0.7 million per km one-way, including equipment, construction, and electric grid costs. These costs are relatively similar to those reported by the 'Slide-In' project, which estimated an eRoad cost of €0.8 million per km one-way for a conductive solution (excluding installation costs) based on trials and existing installations for different trams [12]. Inductive solutions are reporting higher costs, with the Slide-In project estimating a cost of €3.2 million per km one-way based on the Primove technology from Bombardier [13], while Highways England estimated a cost of €2.6 million per km one-way for an inductive solution [26].

In relation to operation and maintenance (O&M), the current suggestion is to assume an annual cost equivalent to 1% of the investment costs based on experiences with similar infrastructure [12], [13], [26], so this is also assumed here. The lifetime of Elonroad is expect to be 10 years, before it is expected to require a refurbishment due to the wear and tear of the switch gear: the on-off switching occurs to ensure that power is only delivered to the road when a vehicle is over it. A lot of the infrastructure will still function after 10 years, but it is not clear what value this will represent just yet. Before finalising the cost assumptions for eRoads, the total annual costs were calculated for the proposed Danish infrastructure in Figure 7 using a variety of investment costs and lifetimes. The results are outlined in Figure 8 and suggest that the total cost of constructing and maintaining eRoads in Denmark ranges from €80-850 million per year, depending on the assumptions applied.

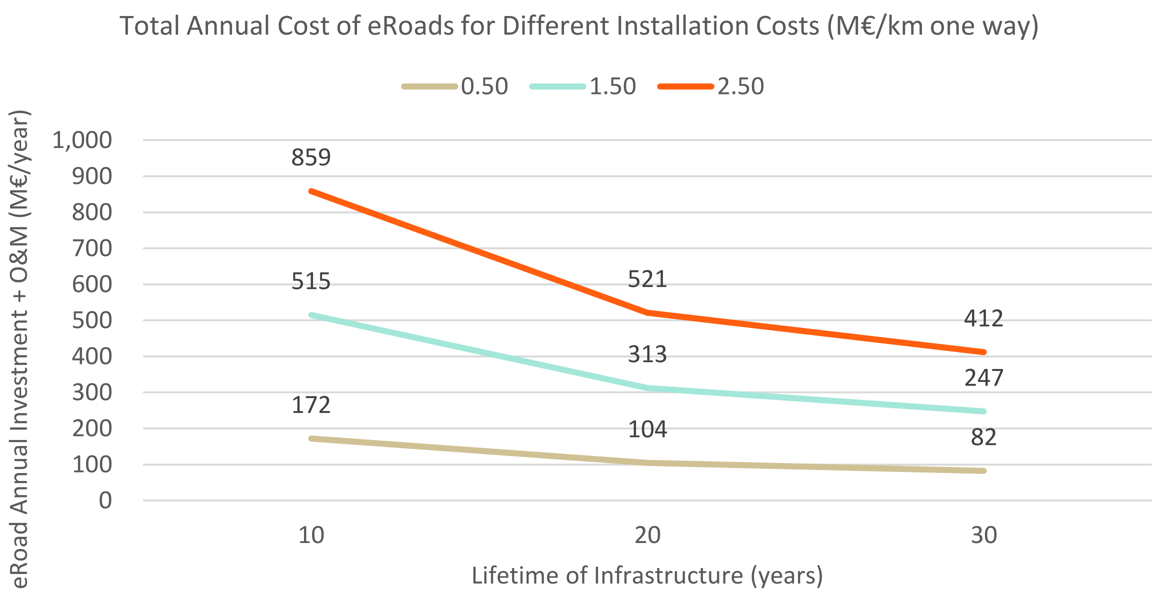


Figure 8: Annual socio-economic investment and maintenance costs to install 2700 km of eRoads in Denmark (see Figure 7 and Table 4) based on a variety of unit investment costs and lifetimes. The calculation is based on an interest rate of 3%, a fixed-rate repayment, and assumes annual operation and maintenance (O&M) costs equivalent to 1% of the total investment [22], [26]**. Elonroad is expected to cost approximately €0.75 million one-way** [36]**. Other sources suggest a cost of €0.8 million per km one-way (plus the installation cost) for a conductive system in Sweden** [12]**, €1.6 million per km one-way for an inductive system in Sweden** [13]**, and €2.6 million per km one-way for an inductive system in England** [26]**. For this study, a unit cost of €1.5 million per km one-way and a lifetime of 10 years are assumed.**

The results in Figure 8 need to be considered in conjunction with the annual energy system costs presented earlier in Figure 3 for the Danish energy system. By comparing the two, it is apparent that eRoads represent a surprisingly small cost in comparison to those for vehicles and fuels in the transport sector. In 2010, the annual vehicle costs in Denmark were almost €10 billion/year whereas the highest cost for eRoads from Figure 8 is approximately €850 million/year. This means that even if the most conservative costs for eRoads are taken from Figure 8, then eRoads would still cost less than 10% of the annual road vehicle costs. In other words, if 10% of the investment spent on road vehicles each year is allocated to the construction and maintenance of eRoads, then it would be enough to pay for the development of 2700 km of eRoad in Denmark.

This is an important finding since it suggests that although the eRoad infrastructure represents a large upfront investment, this investment is relatively small compared to the other expenditure already taking place in the transport sector. Based on this finding, a relatively conservative assumption is used here for the Elonroad system: although the developers expect it to cost approximately €0.75 million per km one-way, a cost of €1.5 million per km one-way is used here instead (see Table 5) and the lifetime of the Elonroad system is assumed to be 10 years for all of the components. Therefore, it is likely that the costs for Elonroad are over-estimated in this analysis.

For the pickup device on the vehicle, the current cost forecasted for Elonroad is €2000 for each car and van and €10,000 for each bus or truck. Again, this seems relatively conservative, since the Slide-In project suggests a cost of €5000 for a truck based on some prototypes that are already developed for conductive connections [12].

In the next section, these assumptions for the eRoad infrastructure are combined with the approach presented earlier for redesigning the transport sector (section 2.1) to compare the economic, energy, and environmental impact of the oil, eRoad, and BEV scenarios for the 2010 Danish energy system.

Table 5: Key assumptions for eRoad infrastructure in this study, based on the Elonroad system [4]**.**

eRoad Investment for a full installation, including electric grid costs (M€/km One Way)	1.5
Lifetime of Infrastructure (years)	10*
Interest Rate	3%
Fixed O&M (% of Investment)	1%
Conductive pick-up for *Cars&Vans* (€)	2000#
Conductive pick-up for *Buses&Trucks* (€)	10,000#
Efficiency transferring electricity from the road to the vehicle (%)	90%

***A 10-year lifetime is relatively conservative, since a lot of the components will last longer than 10 years.**
#The pickup costs are likely overestimated, since a recent study suggest that a pickup is currently available for trucks at a cost of €5000 for a conductive connection. The lifetime of the conductive pick-up is assumed to be the same as the vehicle (see Table 8 in the appendix).

3. Results

The results for the various eRoad and BEV scenarios (in Table 3) are displayed in Figure 9 and Figure 10. As displayed previously in Figure 3, the total annual energy system costs for Denmark in 2010 are approximately €20 billion/year. Since the road vehicles accounted for the largest single component, equating to almost half the overall costs at €9.7 billion/year, these are the only cost presented separately in Figure 9.

Figure 10 illustrates the primary energy supply (PES) and carbon dioxide emissions for the *Ref 2010* scenario, which were 241 TWh/year and 54 Mt/year respectively. The PES and CO_2 emissions are reduced in all scenarios that include increased penetrations of eRoads and BEVs; this is expected since both eRoads and BEVs use more efficient electric vehicles compared to the conventional diesel and petrol vehicles (see Table 7). The results are very similar for *Cars&Vans* for both technologies, with the PES and CO_2 emission both reducing by approximately 5-10%, depending the level of *Cars&Vans* converted.

However, one of the major advantages of eRoads is that they can also facilitate the conversion of heavy-duty transport such as buses and trucks. By converting 50% of buses and trucks to electricity, the PES and CO_2 emissions can be reduced by a further 2%. This is less than expected considering the amount of fuel that is converted to electricity for buses and trucks, but upon further investigation it becomes apparent why.

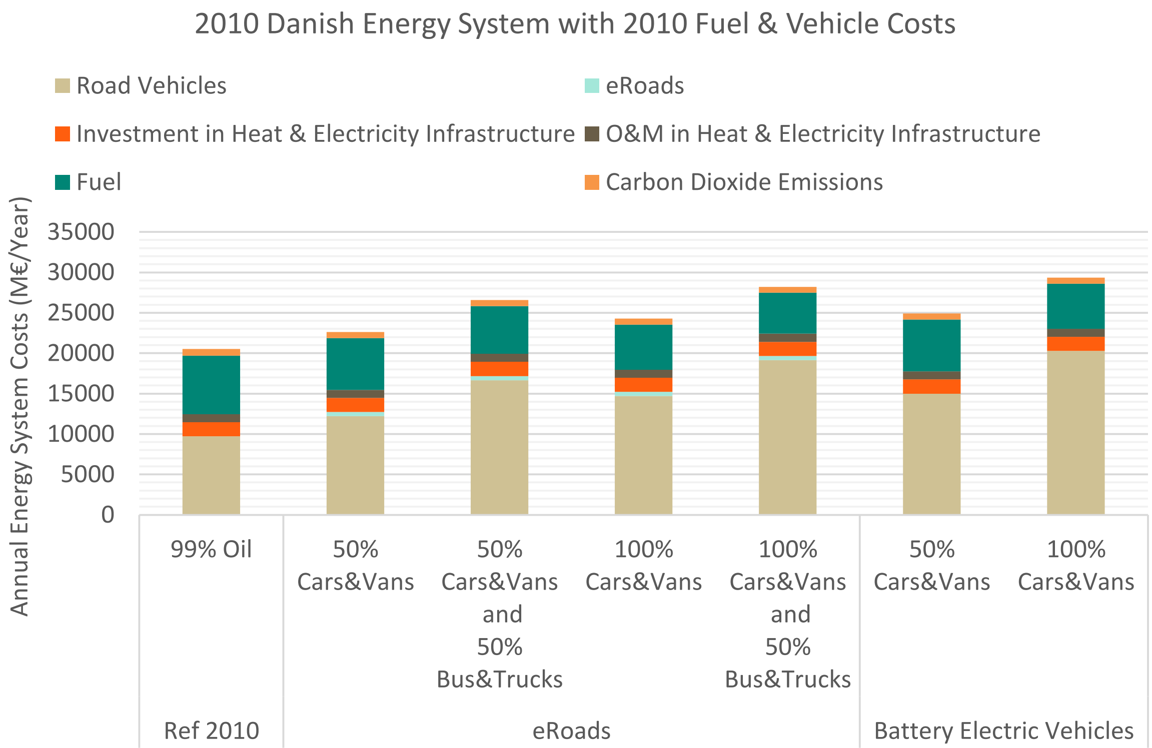


Figure 9: Annual energy system costs for the *Ref 2010* scenario with various penetrations of eRoad and battery electric vehicles, based on the scenarios presented in Table 3 and the eRoad infrastructure proposed in Table 4. The fuel and vehicle costs as based on the year 2010 (see Table 6).

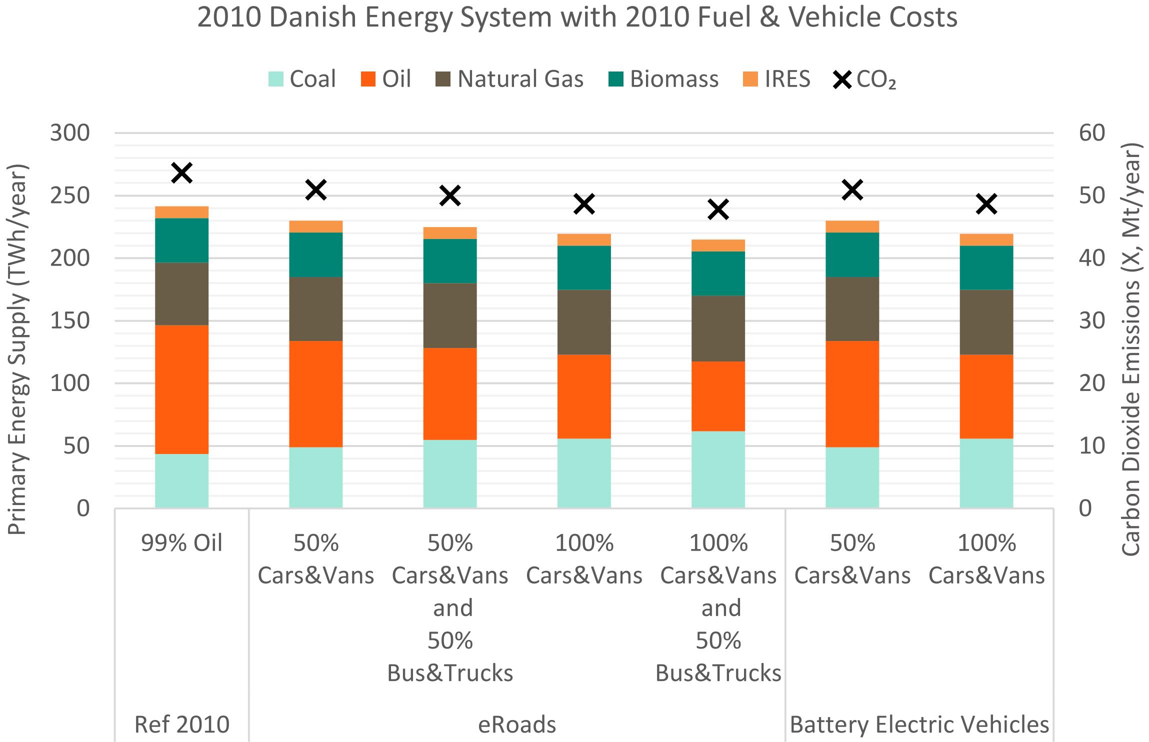


Figure 10: Primary energy supply and carbon dioxide emissions for the *Ref 2010* scenario with various penetrations of eRoad and battery electric vehicles, based on the scenarios presented in Table 3 and the eRoad infrastructure proposed in Table 4. The fuel and vehicle costs as based on the year 2010 (see Table 6).

In each scenario, the EnergyPLAN model will increase the wind power production if it is cheaper to do so. However, due to the relatively low cost of fuel and high capacities of wind already installed in the *Ref 2010* scenario, wind power is not increased in any of the eRoad or BEV scenarios. Instead, the additional electricity is produced by combined heat & power (CHP) and power plants (PP). However, the introduction of eRoads and BEVs does increase the flexibility of the energy system, so from a technical perspective, it is possible to accommodate more wind power if it can be produced at a sufficiently cheap price. This is demonstrated in Figure 11, which presents the amount of curtailed wind energy for each scenario, if a hypothetical 10 GW of wind power is installed in the *Ref 2010* scenario. For context, the *Ref 2010* originally had almost 3 GW of wind power installed that produced approximately 6.3 TWh of wind energy. When this is increased to 10 GW, then almost 14 TWh of wind energy will need to be curtailed out of the 21 TWh of wind power that is produced, so approximately two-thirds. When the same 10 GW of wind power is installed in the eRoad and BEV scenarios, the amount of curtailed wind energy is reduced to between 3 and 5.5 TWh, demonstrating the additional flexibility that is created by the new battery storage introduced in the electric vehicles. Therefore, the relatively low reduction in PES and CO_2 emissions for the eRoad and BEV scenarios is occurring since CHP and PP production is cheaper than additional wind power production in the *Ref 2010* scenario.

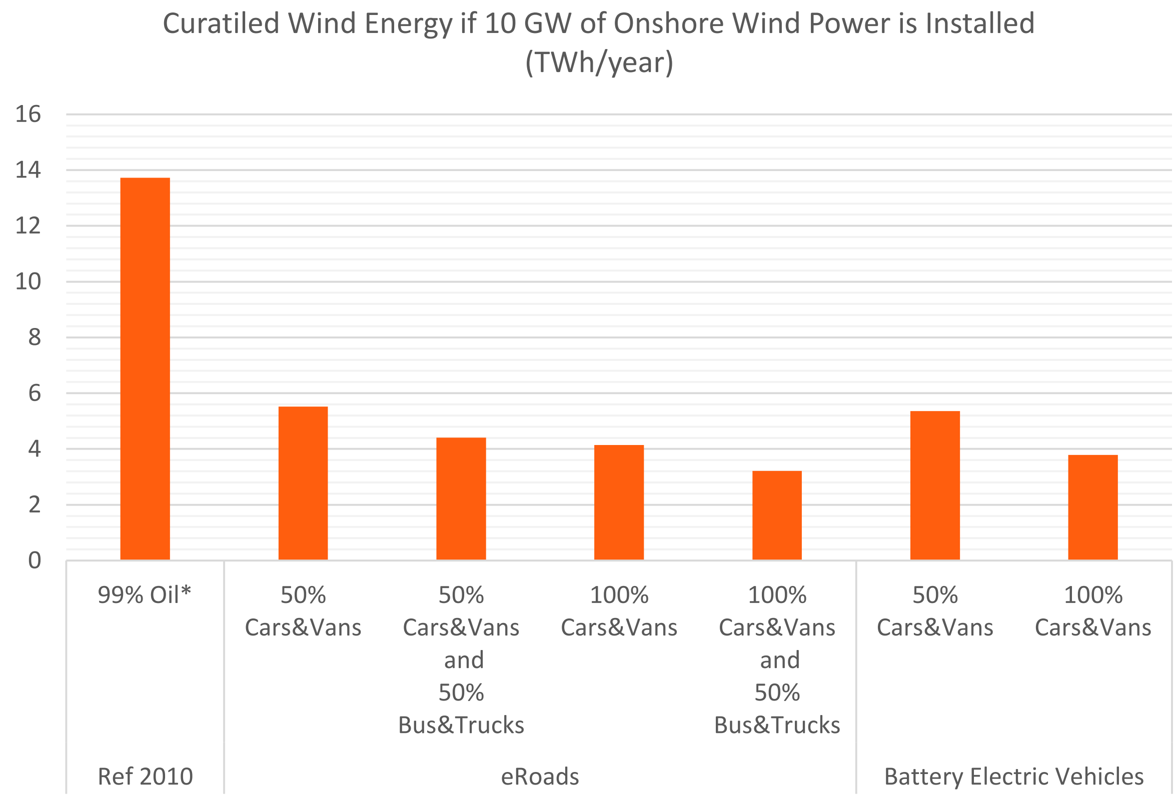


Figure 11: *The *Ref 2010* scenario has an installed wind capacity of 2934 MW which produced 6.3 TWh of wind energy.

In terms of costs, all of the eRoad and BEV scenarios are also more expensive than the *Ref 2010* scenario (see Figure 10). However, one of the key questions that then arises is if the savings in battery costs can exceed the additional cost of constructing and operating the new eRoad infrastructure. Figure 9 indicates that the eRoad infrastructure is cheaper than the additional battery capacity required, since all of the eRoad scenarios are cheaper than the corresponding BEV scenarios. For example, when 50% of *Cars&Vans* are converted to eRoads, then the *Ref 2010* energy system costs increase by approximately 10%, but when 50% are converted to BEVs, then the costs increase by over 20%. This is a very important finding, since it suggests the additional cost of constructing the eRoad infrastructure is less than the additional cost of larger batteries for the BEV *Cars&Vans*, a conclusion which becomes more robust after considering the vehicle costs.

As already highlighted in the context of the *Ref 2010* scenario (Figure 3), the vehicle costs account for almost half of the total energy system costs. As expected, this proportion increases even further in the eRoad and BEV scenarios since these have even higher vehicle costs. When 50% of the *Cars&Vans* are converted to eRoads, then the annual road vehicle costs increase by ~25% which equates to approximately €2.5 billion/year. For the same level of BEVs, the annual road vehicle costs increase by more than double that for eRoads, by over €5 billion/year. Considering the annual cost of the eRoad infrastructure is approximately €500 million/year (see Figure 8), it is clear how the savings in road vehicle cost in the eRoad scenarios are more than sufficient to outweigh the additional battery capacity costs for BEV *Cars&Vans*. Importantly, these results are based on relatively high battery costs since they are from the year 2010 and battery costs are expected to decline significantly in the coming decades (see Table 6). Other costs, primarily fuel, CO_2, and renewable electricity generation are also expected to change significantly in the coming decades: fossil fuel and CO_2 prices are expected to increase and renewable electricity costs are expected to decrease. Each of these key trends will have a significant impact on the scenarios proposed here, so the same scenarios are repeated here using the forecasted 2050 costs in Table 6 as well as Table 8 and Table 10 in the Appendix. It is important to note the *Ref 2010* energy system still forms the basis of the model, since only the costs are updated.

Table 6: Key cost changes between 2010 and 2050. All costs are reported for 2010 and 2050 in the EnergyPLAN Cost Database [40]**.**

<table>
<tr><th colspan="2">Year</th><th>2010</th><th>2050</th></tr>
<tr><td colspan="2">Average Oil Price ($/barrel)</td><td>80</td><td>140</td></tr>
<tr><td rowspan="6">Fuel Prices (€/GJ)</td><td>Coal</td><td>2.7</td><td>3.4</td></tr>
<tr><td>Diesel</td><td>11.7</td><td>19.6</td></tr>
<tr><td>Petrol</td><td>11.9</td><td>19.7</td></tr>
<tr><td>Jet Fuel</td><td>12.7</td><td>20.6</td></tr>
<tr><td>Natural Gas</td><td>5.9</td><td>12.2</td></tr>
<tr><td>Biomass</td><td>5.6</td><td>8.1</td></tr>
<tr><td rowspan="3">Investment Costs (M€/MWe)</td><td>Wind Onshore</td><td>1.1</td><td>0.9</td></tr>
<tr><td>Wind Offshore</td><td>2.85</td><td>2.12</td></tr>
<tr><td>Photovoltaic</td><td>1.02</td><td>0.69</td></tr>
<tr><td colspan="2">CO_2 Price (€/ton)</td><td>15</td><td>45</td></tr>
<tr><td colspan="2">Unit Battery Costs (€/kWh)</td><td>604</td><td>168</td></tr>
</table>

The economic results using the 2050 costs for the *Ref 2010* model with various levels of eRoads and BEVs are presented in Figure 12. For the *Ref 2010* scenario, the total energy system costs increase by almost one-third when the 2050 assumptions are applied, which is almost exclusively due the increasing fuel prices since the annual vehicle costs do not change from before. In contrast, the eRoad and BEV scenarios either increase by less or in some cases even reduce, so the eRoad scenarios are now cheaper than the *Ref 2010* scenario.

The cheapest scenario now occurs when 100% of cars and vans are converted to eRoads, which reduces the cost of the energy system by almost 10% compared to the *Ref 2010* scenario. The cost of this scenario is very similar to the other '*100% Cars&Vans and 50% Bus&Trucks*' eRoad scenario, with a difference of less than 2% between their respective total costs. It is very likely that the primary reason for the higher costs when buses and trucks are converted is due to the relatively high costs of their on-board batteries (see Table 10), but these could be reduced by either installing smaller batteries or by using a hybrid vehicle, which consumes electricity when travelling on an eRoad and fuel during 'off-eRoad' operation. A future study could analyse these alternatives, in combination with a more systematic assessment of what battery capacities are sufficient for buses and trucks to become 100% electric when various routes are converted to eRoads, which is beyond the scope of this study.

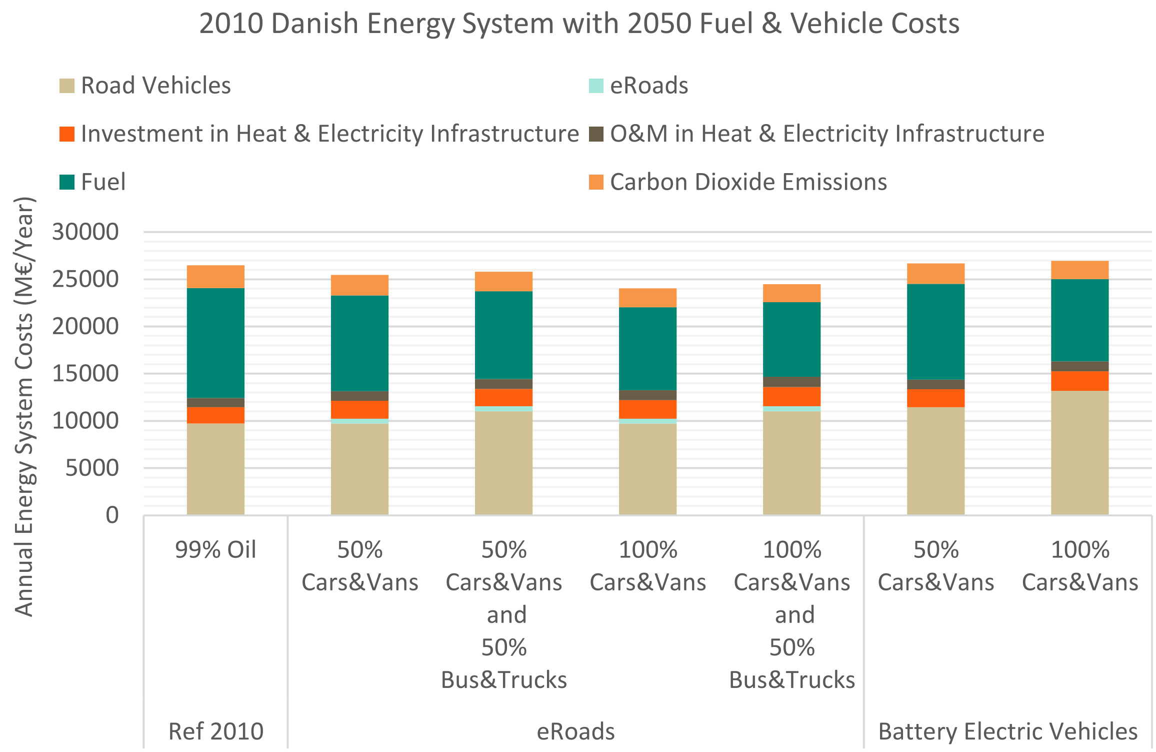


Figure 12: Annual energy system costs for the *Ref 2010* scenario with various penetrations of eRoad and battery electric vehicles, based on the scenarios presented in Table 3 and the eRoad infrastructure proposed in Table 4. The fuel and vehicle costs as based on the year 2050 (see Table 6).

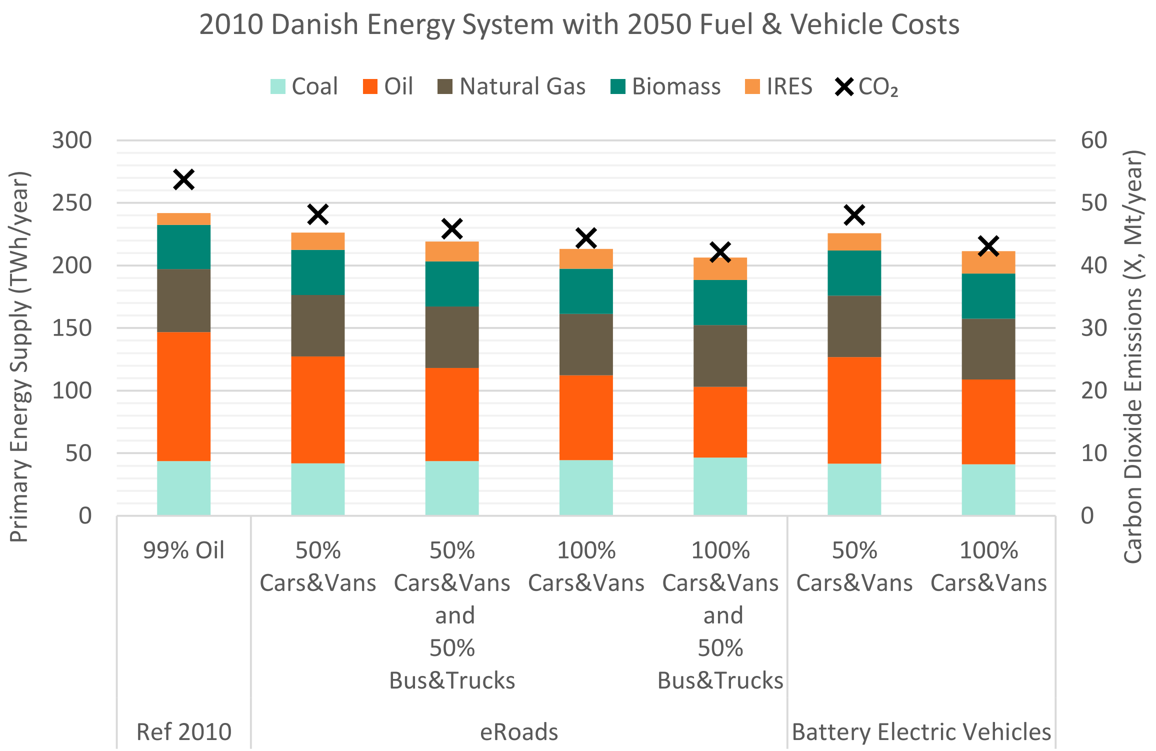


Figure 13: Primary energy supply and carbon dioxide emissions for the *Ref 2010* scenario with various penetrations of eRoad and battery electric vehicles, based on the scenarios presented in Table 3 and the eRoad infrastructure proposed in Table 4. The fuel and vehicle costs as based on the year 2050 (see Table 6).

Importantly, the eRoad scenarios are again cheaper than the BEV scenarios, which suggest that even with the forecasted reductions in battery costs, the eRoad infrastructure is still cheaper than the additional battery capacity required for BEVs. Again, this is reflected in the vehicle costs for each of these scenarios, with the *100% Cars&Vans BEV* scenario having a vehicle cost of over €13 billion/year compared to under €10 billion/year for the *100% Cars&Vans eRoad* scenario. As displayed in Figure 8, the annual cost of the eRoad infrastructure is approximately €0.5 billion/year, so there is a net saving of €2.5 billion/year on vehicle-related costs in the *100% Cars&Vans eRoad* scenario compared to the corresponding BEV scenario. These vehicle-related savings are the primary reason that the eRoad scenarios are cheaper than the BEV scenarios, since from a technical perspective their results are almost the same.

When the cars and vans are converted to either eRoads or BEVs, the PES is reduced by 6-12% for both type of vehicles, and the CO_2 emissions are reduced by 10-20% depending on the amount of vehicles converted (see Figure 13). These savings are larger for the 2050 costs, since there is a lot more wind power in comparison to the scenarios with the 2010 costs. The higher fuel and CO_2 prices in 2050, combined with lower wind prices compared to 2010 (see Table 8) means that higher shares of wind power now result in cheaper eRoad and BEV scenarios. The total wind is increased from just under 3 GW in the *Ref 2010* scenario to 5-7 GW in the eRoad and BEV scenarios, reflecting the fact that wind power is now cheaper than fossil fuels, but also the additional flexibility introduced by eRoads and BEVs. As presented earlier in Figure 11, the additional battery storage in the eRoad and BEV scenarios creates more flexibility in the energy system which enables more intermittent renewables to be accommodated. Now that the cost of wind power is less than fossil fuels, this additional flexibility can be utilised by wind energy with the total wind capacity approximately doubles across the various eRoad and BEV scenarios.

4. Discussion

The results from this study suggest that eRoads are economically viable if the technology develops based on current price forecasts. In all scenarios, eRoads are cheaper than the corresponding BEV scenario, which suggests that for Denmark at least, a combination of eRoads and 'small' battery electric cars is cheaper than 'larger' battery electric cars on their own. Although the eRoad scenarios are more expensive than diesel and petrol today, based on 2010 costs, if battery, vehicle, and fuel costs develop as expected in the future, then eRoads will be cheaper than a continued dependence on oil.

Many key stakeholders in the rail, automotive, electric grid, and road network industries are actively developing various eRoad technologies, which were summarised earlier in Table 1 and Table 2. As mentioned from the outset, the aim in this study is not to predict which one of these solutions will become mainstream, instead it is to analyse the overall feasibility of implementing eRoads in the long-term, particularly in the context of decarbonisation. However, to ensure that the assumptions for the economic and technical performance of the eRoad infrastructure are connected, the Elonroad system is used as a benchmark when defining the expected cost and performance of the eRoad components.

4.1. Economics

One of the most important findings here is the relative scale of the eRoad infrastructure compared to the cost of road vehicles. An extensive eRoad network can be developed and maintained in Denmark at a cost of approximately €0.5 billion/year, while the annual costs for road vehicles is approximately €10 billion/year. Even though the investment costs are very high for eRoads, they are relatively small compared to the combined investment in vehicles each year. Policymakers could utilise this finding by including the eRoad investment in the vehicle cost for consumers. In other words, if a consumer buys an eRoad electric vehicle, then they could pay a fee towards the development of the eRoad infrastructure, since this additional fee will likely be lower than the alternative of buying an electric vehicle with a larger battery.

Within the eRoad scenarios, one surprising finding is that the *100% Cars&Vans* scenario is cheaper than the *100% Cars&Vans and 50% Bus&Trucks* scenario. Although it is not confirmed in the results presented here, it is very likely that this occurs due to the battery costs for buses and trucks, when they are driving 'offline', away from the eRoad routes. A smaller battery in the buses and trucks or otherwise a hybrid vehicle, which continues to use fuel in offline mode, is likely to result in the buses and trucks becoming part of the cheapest scenario. This is important to consider, since there are currently very few affordable ways to decarbonise heavy-duty transport [8], [41] and an over-reliance on biofuels could lead to an unsustainable consumption of biomass [6], [7].

4.2. Energy and Emissions

Cost is also only one of the metrics considered here, since the PES and CO_2 emissions were also analysed for each scenario. As expected, the eRoads and BEV scenarios all reduced the PES and CO_2 emissions compared to a continued dependence on oil: the PES is reduced by 5-15% and the CO_2 emissions by 5-20% depending on the level of electric vehicles assumed. The PES and CO_2 reductions are almost doubled when the 2050 costs are assumed, since an expansion of wind power becomes more economically attractive as a form of electricity production instead of CHP and power plants. The additional flexibility in the electricity system due to the new battery storage in the electric vehicles facilitates the technical integration of this new wind power capacity, so many of the eRoad and BEV scenarios have more than double the wind capacity compared to the *Ref 2010* scenario. No economic gains are included in the analysis here for the increased use of domestic wind power over the import of diesel and petrol for Denmark, so placing a value on this would also improve the cost differential for eRoads.

4.3. Robustness of the Results

Overall, the assumptions here for eRoads are very conservative, which is purposely the case considering the immaturity of the technology. The lifetime of eRoads is limited to 10 years based on some upgrades that would be required if using the Elonroad system, but many of the components will last far beyond 10 years. An investment cost of €1.5 million per km one-way is assumed, but the target for the Elonroad system is currently half of that at €0.75 million per km one-way. The amount of eRoad infrastructure installed in Denmark is very high, since it was designed to ensure that everywhere in Denmark is within 50 km of an eRoad route. Many of the rural routes included are likely to service a very small proportion of the population and trips, especially since it is assumed that each eRoad electric vehicle has a minimum range of 150 km. Although it is not analysed in detail here, it is reasonable to assume that very high penetrations of electric vehicles could occur with less eRoad infrastructure, especially for the scenarios where it is assumed that only 50% of the *Cars&Vans* are converted to eRoads. Similarly, the cost of the pickup device assumed here for the eRoad vehicles is relatively high compared to the costs currently being reported by some demonstration projects. In addition, it is assumed here that the number of vehicles converted is proportional to the amount of transport demand that is converted, which again is conservative, since it is likely that vehicles with relatively high mileage will be the first to start converting since they have the most to gain by switching from oil to electricity. Overall, there are naturally many uncertainties associated with a new technology like eRoads, but these conservative assumptions should provide a relatively high degree of robustness for the conclusions, specifically in relation to the costs. As more information becomes available, especially from the ongoing demonstration and pilot projects, future work can refine many of the assumptions in this study.

5. Implementation

Many of the technologies in the energy system have very long lifetimes, such as power plants, which have lifetimes of ~30 years; energy networks usually operate for ~40 years; and hydroelectric plants can stay operational for over 50 years. Changing infrastructure with a lifespan over many decades is very challenging, since it is difficult to justify shutting them down before they reach the end of their lifetime due to the sunk costs, and when the opportunity does arise to replace it at the end of its lifetime, it usually requires a very large upfront investment in a new alternative. In contrast, vehicles have a relatively short lifetime.

In this study, *Cars&Vans* have an assumed lifetime of 16 years while it is 6 years for *Buses&Trucks*. This means that the majority of the vehicle fleet is replaced on a 16 year cycle, so if a new solution like eRoads is developed, then the opportunity to replace the vehicle fleet will arise relatively quickly compared to other technologies in the energy system. Therefore, although the transport sector faces significant challenges to overcome its dependence on oil, the lifetime of these vehicles suggests that a new solution could be implemented relatively quickly compared to other sectors.

5.1. Challenges and disadvantages

There are many challenges that need to be considered in relation to eRoads. For example, a commercial version of the technology has yet to be developed on a large scale so a lot of research is still required to go from the concepts proposed to a final working solution. It is unclear how these solutions will perform during road maintenance (i.e. roads need to be resurfaced) and after accidents: for example, if one section of the eRoad infrastructure is damaged, will it shut down an entire section of the infrastructure and thus leave some traffic stranded. The infrastructure will also need to deal with the weather, particularly surface water, frost, and snow. Even if eRoads can be developed and installed at a price that is cheaper than the alternatives, it will still be difficult to implement the technology since it requires a radical change in the transport sector. For example, eRoads could reduce the profitability of existing actors in the transport sector and new institutions will be necessary to install, operate, and maintain the eRoad infrastructure.

There are also many potential disadvantages that need to be considered in relation to eRoads. For example, batteries may develop faster than expected and thus the infrastructure may not be necessary, although this is unlikely based on current price forecasts. There may be cheaper alternatives such as car-sharing and public transport (i.e. electric rail) and there may also be a significant rebound effect due to the increased comfort levels and cheaper fuel prices associated with eRoads. This could lead to congestion especially in densely-populated urban areas which are at the end of the routes with eRoads installed. If eRoads ever become a mainstream form of transport, these issues and many others will still need to be considered.

5.2. Additional Benefits

If eRoads are implemented on a large scale, then it is important to consider advantages beyond the metrics considered here such as costs, energy, and carbon dioxide emissions. As discussed in a previous study [8], electricity is the most sustainable form of fuel for transport. Furthermore, electricity is the highest quality of energy that is currently available, since it can be used in a ‘smart’ way in a range of electronic devices. Due to these characteristics, an eRoad could enable a number of additional advantages such as:

- Drivers will no longer need to refuel since the vehicle can be charged at home and while driving.
- Increased security of supply: Electricity from local renewable resources can be used for electric vehicles instead of importing large volumes of oil for the transport sector, which is currently the case for the majority of developed countries [46]. eRoads could even be installed in conjunction with Solar Roadways [42] and produce some of the electricity required for the electric vehicles itself.
- Road vehicles could communicate with one another while connected to the electric road. This should increase the utilisation of the road network and improve traffic flow. It could also facilitate more carpooling since it would be easier to track where vehicles are located on major road routes.
- The eRoad infrastructure could be used to enhance telecom networks, by using these new power lines to extend fixed line communications and potentially, by extending wireless communication through the use of the vehicles themselves.
- Installing a fixed power line on the road could also facilitate the introduction of self-driving cars such as those being developed by BMW [47], Google [48], and Victoria Tech University [49]. If eRoads are installed on major routes, then vehicles could use eRoads as a guide for the vehicle to follow, which would reduce the need for advanced radar and GPS systems on the self-driving vehicles currently being proposed.

6. Future Work

In many cases, long-term energy planning revolves around the expansion of an existing technology, rather than the introduction of a completely new one. In this study however, eRoads represent a radical technological change since the current developments are all at research, lab, demonstration, or trial phase. As such, many of the assumptions need to be improved in future work, especially in relation to the expected costs. A sensitivity analysis is included here for what was perceived to be the most essential cost assumptions; fuels, CO_2, batteries, and renewable electricity; but future work could include many more such as various eRoad designs and driving patterns, eRoad investments, maintenance costs, pickup costs, and various battery capacities for the eRoad vehicles. Furthermore, all of these costs are adjusted together in this study, but future work could analyse the impact of these changes individually.

Similarly, this study includes a 2010 energy system model of Denmark, *Ref 2010*, which is adjusted based on six different electric vehicle scenarios: four for eRoads and two for BEVs. Future work should include a future energy system model for Denmark, such as 2030 or 2050. A future scenario is not included here since there is already a lot of uncertainty in relation to eRoads without adding the additional uncertainty of how the energy system will evolve. Since the conclusion here is that eRoads could be an economically viable technology for the decarbonisation of road transport, future work should also consider how eRoads will fit in the future energy system as well as todays, across various countries and eRoad network designs.

This study is also restricted to three main alternatives for transport: oil, eRoads, and BEVs. Other alternatives should be compared with eRoads in the future such as biofuels, hydrogen, and electrofuels. It is likely, especially for buses and trucks, that a combination of eRoads with some form of ‘offline’ fuel such as biofuels or electrofuels could result in a cheaper energy system than any of the scenarios identified here. The scenarios developed here represent extreme cases based on oil and electricity, so future research could analyse variations between many of these. Therefore, there are still numerous institutional, social, technological, and economic challenges still to be overcome, but the results in this study indicate that further investigations are warranted. More specifically, the finding here that eRoads are more economically viable than BEVs means that future work should consider eRoads as an important alternative for decarbonising the transport sector.

7. Conclusions

The primary objective in this study is to investigate the economic feasibility of a radical technological change in the transport sector, eRoads, which will facilitate the use of electricity in all modes of road transport instead of oil. Using Denmark as a case study, a number of important findings were identified. Firstly, the scale of the transport sector became apparent during the early stages: transport represents one-third of the energy consumed in Denmark and two-thirds of the annual energy system costs. Changes to the transport sector therefore have a major impact on the overall performance and cost of the energy system.

The costs are particularly relevant in this study, since one of the main objectives with eRoads is to reduce the size, and therefore cost, of the battery required in electric vehicles. The eRoad scenario developed here for Denmark requires 2700 km of eRoad infrastructure to be installed so that everywhere in the country is within a 50 km distance of an eRoad route. The cost of installing and maintaining this infrastructure is calculated here using the Elonroad technology as a benchmark, resulting in an annual cost of approximately €500 million/year and an upfront investment of approximately €4 billion. This is relatively small compared to the vehicle costs: the annual road vehicle costs in Denmark were almost €10 billion/year in 2010, so installing eRoads would only increase this by approximately 5%. This suggests that a collective solution like eRoads could realistically be developed by replacing some of the individual investment in vehicles with a public eRoad infrastructure.

Due to the relatively low cost of eRoads, the results also indicate that they are a cheaper method of electrification than Battery Electric Vehicles (BEVs). Historical battery costs based on the year 2010 and forecasted battery costs for the year 2050 are both included in this study, since the 2050 costs are less than one-third of the 2010 costs. In both scenarios, the eRoad scenario is cheaper than the corresponding BEV scenarios, since the cost of developing the eRoad infrastructure is less than the additional costs of providing on-board battery storage in the vehicles. Furthermore, eRoads enable heavy-duty road transport to be electrified such as buses and trucks, which are unlikely to be electrified using batteries alone due to the very large costs.

Using the 2010 costs, the eRoads scenarios are more expensive than oil vehicles (i.e. diesel and petrol), but if the cost of fuel, CO_2, batteries, and renewable electricity evolve as expected, then the 2050 results suggest that eRoads will be cheaper than oil in the future. In both the eRoad and BEV scenarios, it is possible to integrate more renewable electricity due to the additional flexibility introduced by the on-board batteries: however, this only occurs using the 2050 cost assumptions since other forms of electricity production were cheaper when the 2010 costs were applied.

This is the first study that has ever analysed the economic impact of implementing eRoads on a national scale so there are a number of areas that need further research before concluding that eRoads are the optimum solution. However, the results here indicate that further research is warranted and that eRoads should be considered as an important alternative in future studies when evaluating how to decarbonise the transport sector. Various forms of eRoad solutions are currently being developed, so it is likely that more robust economic and technical data will become available in the coming years as various pilot and demonstration projects begin.

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9. Appendix

Table 7: Detailed breakdown of the Danish transport sector in 2010 [2], [10].

Vehicle Type	Transport Demand (Mkm)	Number of Road Vehicles	Vehicle Efficiency (kWh/km)	Transport Fuel Consumption (TWh/year)
Cars	34,543	2,120,073	0.7	25.5
Diesel	9,862	428,442	0.7	7.3
Petrol	24,508	1,681,029	0.7	18.1
Bioethanol	86	5,301	0.7	0.1
Biodiesel	86	5,301	0.7	0.1
Battery Electric	0	0	0.1	0.0
eRoad Electric	0	0	0.1	0.0
Vans	8,451	462,260	1.3	11.3
Diesel	7,226	380,484	1.3	9.6
Petrol	1,183	79,648	1.3	1.6
Bioethanol	0	0	1.1	0.0
Biodiesel	42	2,128	1.3	0.1
Battery Electric	0	0	0.2	0.0
eRoad Electric	0	0	0.2	0.0
Buses	616	14,509	6.5	4.0
Diesel	614	14,445	6.5	4.0
Biodiesel	3	64	6.5	0.0
Battery Electric	0	0	1.4	0.0
eRoad Electric	0	0	1.4	0.0
Trucks	1,812	69,518	10.7	19.3
Diesel	1,804	69,212	10.7	19.2
Biodiesel	8	306	10.7	0.1
Battery Electric	0	0	2.6	0.0
eRoad Electric	0	0	2.6	0.0

Table 8: Vehicle cost assumptions for 2010 and 2050 [2].

	Year	2010			2050		
	Vehicle	Investment (€/vehicle)	Annual O&M (% of Invest)	Lifetime (Years)	Investment (€/vehicle)	Annual O&M (% of Invest)	Lifetime (Years)
Cars and Vans	Diesel	21,560	3.9%	16	21,560	3.9%	16
	Petrol	19,560	4.3%	16	19,560	4.3%	16
	Otto Motor	21,513	3.9%	16	21,513	3.9%	16
	DME	22,535	3.8%	16	22,535	3.9%	16
	Battery Electric*	20,490	24.0%	16	18,055	13.1%	16
	eRoad Car	22,490	11.5%	16	20,055	4.3%	16
Buses	ICE Diesel	177,184	9.1%	6	177,184	9.1%	6
	Biodiesel	177,184	9.1%	6	177,184	9.1%	6
	Battery Electric*	177,184	148.3%	6	177,184	49.7%	6
	eRoad Electric	187,184	43.5%	6	187,184	20.2%	6
Trucks	ICE Diesel	99,220	21.1%	6	99,220	21.1%	6
	Biodiesel	99,220	21.1%	6	99,220	21.1%	6
	Battery Electric*	99,220	473.2%	6	99,220	146.7%	6
	eRoad Electric	109,220	121.8%	6	109,220	47.7%	6

*The battery costs are included in the annual O&M costs, since it is assumed that the battery lifetime is half of the vehicle lifetime.

Table 9: Electric Vehicle Assumptions which are the same for 2010 and 2050 [2], [26], [36].

Type of Vehicle	Battery Electric	eRoad Electric		
	Cars and Vans	Cars and Vans	Buses	Trucks
Power Capacity (kW/vehicle)	30	30	200	200
Storage Capacity (kWh/vehicle)	54	27	283	525
Battery Life (Years)	8	8	3	3
eRoad Vehicle-to-Road Connection Cost (EUR/vehicle)	n/a	2000	10,000	10,000
Additional Battery Capacity to Avoid Deep Discharge (% of Original Capacity)	+35%	+35%	+35%	+35%

Table 10: Electric Vehicle Assumptions which vary between 2010 and 2050 [2].

		Type of Vehicle			
		Battery Electric	eRoad Electric		
	Year	Cars and Vans	Cars and Vans	Buses	Trucks
Distance to Cover with Battery (km)	2010	300	150	150	150
	2050	500	150	150	150
Battery Capacity (kWh)	2010	54	27	283	525
	2050	90	27	283	525
Unit Battery Cost (EUR/kWh)	2010	604	604	604	604
	2050	168	168	168	168